AN INVESTIGATION OF THE EFFECTS OF GRAIN SIZE AND VOIDS-RATIO ON THE THERMAL CONDUCTIVITY OF SAND

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PART I

INTRODUCTION

INTRODUCTION

Although the effects of heat transfer through and into the earth's crust are of prime importance to man, scientific investigations of the thermal conductivity of soils are recent of origin and limited in scope. Through the centuries man's use of soils has been based upon instinct and experience, rather than upon knowledge and understanding.

The agriculturalist is concerned with the conduction of the suns heat below the surface of the ground to promote plant growth. The electrical engineer depends on soil conductivity to remove heat from buried electrical cables and thus protect and preserve their insulation. Instead of simple reliance upon the soil surrounding electric cables to perform this function, attempts have been made (3) to increase the thermal conductivity of the soil, increasing and accelerating heat transfer.

Engineers in the building trades are concerned with heat transfer and the selection of materials for their heat insulation value. Much construction is subsurface and the new field of radiant heating is largely dependent upon heat conduction through soil. The U. S. Army Engineers are experimenting with below ground bomb defense structures whose heating will be influenced primarily by this factor.

Procedures of design in the above engineering fields commonly allow for heat conductivity by a simplifying design assumption frequently based upon inadequate experimental verification. Even though the value assigned to heat conductivity of soil may be a primary factor in the selection of the final design, once the proper allowance has been made the effect of this property is no longer critical.

A basically different situation faces the soil, foundation, or highway engineer. These men must predict the effect of soil properties upon the soil itself, because many changes of the soil are transmitted directly to the supported structure.

It is well known that soil engineering is intensively concerned with the effects of moisture in all soil properties. Dry soil is experimentally uncomplicated and predictions about dry materials are quite accurate. This cannot be said for moist soil, especially clays, and many investigations in all branches of soil mechanics are being conducted to broaden the knowledge of the effect of moisture on soil.

Examples of the problems resulting from soil moisture and heat transfer will be given. Primary among these problems is that of frost heaving of highway and airport pavements. This condition is caused by the freezing and attendant expansion of ice lenses formed below the pavement. Capillarity supplies water from the ground water

source below, and the freezing of the lenses is the result of heat loss from the ground surface. The rate of heat loss, the total depth of frost penetration, and the rate of lens formation, are dependent upon the thermal conductivity of the soil.

The increasing importance of Alaska in military and defense programs focuses attention upon other cold weather construction problems. Most of Alaska is in that area of the earth's surface which is permanently frozen. This is called "permafrost" and consists of moist soil in which the moisture is frozen and extends into the earth a distance to include the foundations of all structures. Bearing capacity of this "permafrost" is adequate, and no problem arises until the internal heat of the structure is conducted into the material surrounding the foundation causing ice to melt and the structure to settle. Research in this field (2) is being conducted for the U. S. Army Engineers to determine the specific heat, heat capacity, and heat conductivity of various soil components, and to investigate other physical properties which may affect these factors.

The above examples are given to indicate the extent of the field in which information about soil heat conductivity is desired.

There is no easy or satisfactory evaluation of any unknown property of a material so admittedly heterogeneous as soil which would be accepted without an adequate investigation of the known or suspected

variables. It also is evident that these variables must be investigated, first separately, and then in conjunction with each other, in order to present a true and well-based solution. For instance, it would be unreasonable to attempt to reach rational conclusions about the variables causing experimental differences among selected permafrost samples. Before frozen samples are tested, moist unfrozen soil must be understood. Before that, the components of the moist soil must be investigated. In the last analysis, the work can only be started by a thorough investigation of all known variables in the dry soil elements.

To carry out the intent presented in the above discussion, the experimentation was started on the least complicated of the soil components, i.e., dry sand. Preliminary work had been conducted at Rensselaer Polytechnic Institute on a well graded dry sand sample, and it was decided that all possible variables be eliminated from this data by dividing the sand with its broad grain size classification of coarse, medium and fine, and determining a curve of thermal conductivity versus voids-ratio for each of these three sizes. To provide an experimental background for subsequent work in active materials, a test of graded dry clay was conducted.

It is intended that these data will serve as background in elimination or explanation of variables encountered in the determination of thermal conductivity

of natural soils in any of their progressively complex forms. It is to be noted that a double purpose may be served by these investigations. The phenomenon of electro-osmosis (4) is under intensive study by many scientists. There is a close resemblance of many thermal and electrical properties and effects. By establishing a satisfactory dry sand and clay background upon which an investigation of moist samples can be based, it may be possible while investigating the effect of moisture upon heat transfer to obtain data as to the effect of heat upon moisture transfer and thus furnish experimental substantiation and evaluation of the theory of thermo-osmosis.

The work contained herein, is a continuation of "An Investigation of the Effects of Voids-Ratio on the Thermal Conductivity of Sand" by Herbert Storch. The equipment was prepared by Storch as a variation of that used by the United States Bureau of Standards and with it he conducted tests on a well graded dry sand sample.

Since this work is a continuation of previous work using the same apparatus, it follows that there should be much similarity and duplication of technique and of course an identical background. If Storch had been proved wrong there would have been a clear field in which to work in correcting such fallacies, but in several preliminary tests a very close agreement was obtained with his results. Values of thermal conductivity determined

by Storch were also reasonably close to values having been obtained by other investigators. In view of these facts, we must assume Storch to be correct in his preliminary research and in the theory behind his thesis and not attempt to alter his findings but merely to use and broaden them. However, in order to render this a complete work as far as we have proceeded to date, it seems necessary that we do borrow extensively from Storch as to background and theory.

PART II

THEORY

THEORY

Because the problem at hand is one of heat flow, the following three basic laws governing the flow of heat in a body (5) are applicable:

1. The quantity of heat in a body is proportional to the mass and the temperature of the body.

II. Heat flows from a higher to a lower temperature.

III. The rate of heat flow across an area is proportional to the area and to the existing temperature gradient, i.e., the rate of change of temperature with respect to distance, measured normal to the area.

Both in theory and in experimental application a steady-state heat flow condition is assumed. This assumption means that the rate of heat flow is independent of time. Application of laws I and II gives the following values in the c.g.s. system of units:

q (calories/sec.), a constant quantity of heat flowing through A in each second.

A (cm.2), an area perpendicular to the direction of heat flow.

T (°C), the temperature at a point P of the body.

x (cm.), the distance, measured positively

in the direction of flow, from some point selected as an origin to the point. P.

Law III may then be expressed: The magnitude of q equals KA(dT/dx), where K, the constant of proportionality, is a property of the material of the body called its thermal conductivity. K has units cal./cm. deg. sec. Law II states, however, that temperature decreases in the direction of flow making dT/dx negative, and we have, therefore

$$q = - KA\, dT/dx \qquad \ldots\ldots 1$$

Thermal conductivity, K, may be defined as the quantity of heat that flows through a unit area of unit thickness in unit time under unit temperature gradient, and in the c.g.s. system, the K of a substance is the number of calories transmitted in one second between opposite faces of a cubic centimeter of the substance when a temperature difference of one degree centigrade exists across the faces. Similarly, in the f.p.s. or English system, the K of a substance is the number of Btu's transmitted in one second between opposite faces of a cubic foot of the substance when a temperature difference of one degree Fahrenheit exists across the faces.

Application of Buckingham's theorem and the method of dimensional analysis (6) yield equations identical with the equation 1 as shown above. As a

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

basis for calculations of conductivity values of dry sands and clay samples in subsequent work, a more familiar and useful form of equation may be derived. It is set up as follows (1): Let the temperature on each side of a section of the material in question be designated as T_1 and T_2 respectively, the thickness of the section be d, and the amount of heat flowing in time t be equal Q. The rate of heat flow is then Q/t and the temperature gradient is $(T_1 - T_2)/d$. Therefore, according to the above derivations and the definitions given:

$$K = \frac{Qd}{At\,(T_1 - T_2)} \qquad .....2$$

Patten (7,1) visualized the flow of heat through a substance in a somewhat different manner. To borrow from Patten, let us consider the following line of reasoning. Start with a metal bar under conditions of steady-state heat flow with opposite ends of the bar at temperatures of 100°C and 0°C. Consider an elemental section within the bar, letting the element have cross-sectional area A normal to the direction of heat flow and thickness Δx. If the section is x distance from the hotter end of the bar, and if temperature T exists on the area A, the heat flow per unit time through A will be equal to $-KA(dT/dx)$. See equation 1. The surface of the elemental rectangle at distance $x + \Delta x$ from the hotter end of the

bar will have a lower face temperature equal to $T - (dT/dx \ \Delta x)$. The quantity of heat flowing through the surface of the section $x + \Delta x$ from the source will be equal to $-KA \left[d/dx(T - (dT/dx) \Delta x) \right]$. The expression within the brackets is the rate of change of temperature at $x + \Delta x$. Since the temperature at $x + \Delta x$ is lower than at x, there will be less heat leaving the rectangular section than entering. This difference is given by the expression $- KA(dT/dx) - \left\{ -KA \left[d/dx(T - (dT/dx)\Delta K \right] \right\}$ which reduces to

$$- KA \frac{d^2T}{dx^2} \Delta x \qquad \ldots\ldots 3$$

The second derivative of temperature with respect to distance from the heat source is a rate of change of temperature gradient or the acceleration of temperature change with distance. When a steady-state flow exists, gradient is constant and acceleration is zero; there is no difference in the amount of heat entering and leaving a section.

Let us now apply these principles to a body of soil. Before steady-state conditions are reached, unbalance of heat flow exists. Let the mean temperature of a section of soil rise by increment of temperature dT in time dt. If c is the heat capacity of the soil, a quantity of heat equal to $Ac\ (dT/dt)\Delta x$ will be required to cause the rise of temperature. Heat capacity c is equal to the effective specific heat

divided by the apparent specific volume. Assuming no loss of heat from the section under experiment, we can equate this quantity of heat necessary to raise the temperature to the heat remaining in the section, as given by equation 3.

$$Ak\left(\frac{d^2T}{dx^2}\right)\Delta x = Ac\left(\frac{dT}{dt}\right)\Delta x$$

or

$$\frac{K}{c}\left(\frac{d^2T}{dx^2}\right) = \frac{dT}{dt} \qquad \ldots\ldots 4$$

The term K/c has been called "diffusivity" by Patten Equation 4 shows that heat conductivity K may be calculated from the following data: effective heat capacity c, the rate of change of temperature gradient dT/dx, and the change of temperature at a given point with time dT/dt.

The basic concept of heat flow in a homogeneous solid or gaseous medium is the familiar physical principle of heat agitation of molecules, their impinging one on the other, and transferring motion and heat through the medium. Extension of this concept to soils introduces complications. It must be recognized that the heat conductivity of dry sand, for example, depends upon two media, one a solid and the other a gas. Heat flow in dry sand is across sand grains and interstitial air. Since dry air is one of the most effective heat insulators, the path

of conductivity is primarily through the sand grains. As has been shown, the area of conduction plays an important role. Grain size, shape, and proximity should, therefore, be considered. Segregation of a particular type of sand, such as Cow Bay or Port Jefferson, into subdivisions by grain sizes is clearly an aid to analysis of experimental results. Sand grains vary in shape from spherical to fragmental and angular. Port Jefferson sand is chiefly quartz and almost entirely free from organic matter. The samples tested in these investigations are essentially slabs of soil, artificially created and controlled by selection of material, by the manner of placement, and by the amount of compaction. In the case of heat conduction it is readily evident that the farther apart the soil particles are, the lower will be the thermal conductivity. Low thermal conductivity can be expected in loosely compacted, high voids-ratio sand masses; and, conversely, greater compaction, careful grading, and the use of fine-grained materials increase thermal conductivity.

Mention must be made of convection and radiation, as well as conduction. The effects of radiation upon the experimental method used is negligible. In the case of convection, Fecheimer (3) has stated that 0.1" is the maximum size of pore space in which conduction predominates over convection. Only in the most loosely compacted, ungraded samples of coarse sand and gravel will convection occur.

A definition of electro-osmosis as a background for discussion of the thermo-osmosis theory, will be briefly stated. Electro-osmosis is the phenomenon occurring when an external electromotive force is applied across a solid-liquid interface, causing the movable diffuse layer of the Helmholtz double layer to be displaced tangentially with respect to the fixed layer. When this movement occurs in a capillary, the water present in the capillary will be pulled along with the moving diffuse layer and be discharged from the capillary. Thermo-osmosis, then, is the phenomenon which causes capillary flow of water when a soil mass is exposed to a difference of heat potential, i.e., temperature.

PART III

APPARATUS

APPARATUS

The apparatus for measuring thermal conductivity of soil samples will be described. For measurement of thermal conductivity during steady state heat flow, the following must be known about the sample:
(1) the cross-sectional area normal to heat flow,
(2) the thickness in the direction of heat flow,
(3) the quantity of heat flowing through the sample per unit of time, (4) the temperature of both faces, or the temperature difference between both faces of the sample. From these data, the coefficient of thermal conductivity may be calculated.

The apparatus is a variation of that type used by the U. S. Bureau of Standards for measurement of thermal conductivity. Such apparatus is known as a "shielded hot plate" in which a slab of the solid material under test is inserted between an electric hot plate and a cooling plate. Heat flow is measured by the power input and temperature of the plates. Heat flow in a direction not normal to the face of the sample is prevented by an electrically heated guard ring - thus the name "shielded". It was this principle which has been adapted to the measurement of thermal conductivity of dry soil samples.

The equipment is designed as a central heating plate transmitting heat equally in both directions through two soil samples to two cooling jackets.

The end losses are controlled by an insulating box fitting around the edges of the plates and sample holders. The cavities for holding the soil sample are 20 inches square and two inches thick and the dimensions of the plates and other details of the equipment are dependent upon this size. The sample size of 20" x 20" x 2" is large enough to allow manipulation of the material in place and also is of such a size so that end variations have little effect on the center of the sample where temperature measurements are taken.

The heater plate itself is also of a sandwich type of construction. The heating element is Nichrome resistance wire 5/8" wide and .0056" thick. The resistance of this wire is .156 ohms per foot. Twenty turns of this wire are wrapped around a 1/4" thick piece of transite 20" square, the edges of which are notched to hold the wire in position. The resistance of the complete heating element is sufficient to produce a temperature of 100°C easily within the range of voltage available. A frame to hold the heater element is made of a 21" x 21" x 1/4" transite piece with a 20" x 20" square cut out of the center. Heavy copper leads extend through slots cut in this frame and are soldered to the heater element. The outsides of the heating plate are two copper plates 21" x 21" x 1/8" and are electrically insulated from the heating element by sheets of mica .015" thick and 21" square.

The width of the heating element wires and the thickness of the copper plates are sufficient to give a very uniform heat distribution across the face of the plate. The entire unit is held together by binding screw posts and when assembled is 21" x 21" x 5/8" with the two copper leads extending out of either end of one edge of the plate. See Figure VIIIc.

The cooling jackets are constructed of a heavy copper plate 21 1/4" x 22 1/2" x 1/8" to which is soldered a dished out piece of light gage copper forming a water reservoir 20" x 20" x 3/4". Inlet and outlet pipes of ½" copper tubing are soldered in position on two diagonally opposite corners of the cooling reservoir and a system of baffles is installed in each jacket to provide a more uniform distribution of the cooling water which enters at a lower corner and flows out an upper corner.

The cooling jackets are mounted on either side of a 3 sided wooden frame forming an open box with interior dimensions 21" x 20½" x 4 5/8". The pieces forming the frame are 4 5/8" wide and 3/4" thick plywood. Twelve holes are drilled through the width of the plywood frames matching holes around three edges of the cooling jacket and the unit is then assembled by means of 1/4" machine bolts 5½" long. The unit is oriented with the open end of the box on top and the cooling jackets vertical. The heater plate is inserted vertically in the box midway between the cooling jackets and is held in position by

six hardwood spacer boards 2" wide and ½" thick that fit against the frame and are held in place by pressure when the jackets are bolted in place. These spacer boards also provide for an accurate two inch sample width when the entire sample holder unit is assembled and, as was previously stated, the dimensions of the component parts were so chosen that the resulting sample size is 20" x 20" x 2". Also, it can be seen that the dimensions of the heating element and the water jacket of the cooling unit are 20" x 20" and these are so oriented in the assembled equipment that the outline of the sample is accurately covered by the heating and cooling elements and thus the sample is directly in line with heat flow from the hot face to the cold face.

Heat losses from the ends of the sample are prevented by an insulating box. In the equation for heat flow $Q = K\ A\ \Delta t$ the two variables controlling the heat flow are K and Δt. The guard ring of the shielded hot plate reduced Δt to zero but this control is quite complicated and the method of lowering K to a small value is used in this equipment. The insulating box provides for 6" of insulating material inside a wooden box. The box is constructed as a square ring surrounding the edges of the sample box. The top side of the insulating box is removable and forms a cover which may be removed in order to expose the sample

while the sample box remains enclosed by the other three sides of the insulating box. This cover has a slot which receives the $\frac{1}{2}$" of the heating plate extending above the sample and has two holes drilled through it to receive the leads extending from the heating element mentioned above. The insulating material is No. 1 white waste.

The cooling water is supplied to the jackets and led off through $\frac{1}{2}$" rubber tubing. A T connection at the source of water is utilized to equalize the flow through each face.

Temperature measurements are made by the use of thermocouples. It is possible to measure the temperature at a point or on a face much more accurately and simply by this method than by any other. Since the points of measurement are in the center of the faces of the sample, thermocouples offer the only practical method of temperature determination.

The thermocouple material used is Leeds and Northrup #30 gage copper-constantan duplex thermocouple wire which is satisfactory for temperatures of less than 100°C and is simple to install. This wire contains one strand of copper and one of constantan insulated from one another in a fiber casing.

The bare thermocouple wires are embedded with solder in holes drilled 3/16" in diameter and 1/16" deep into the center of the hot and cold plate faces.

It is assumed that the temperature gradient across 1/16" of copper is negligible to the accuracy required by this work and that the temperature of the sample at the face is the same as that of the plate.

The temperatures indicated by the thermocouple millivolt output were measured in two potentiometers. The hot and cold face temperatures of one sample were measured by an automatic potentiometer recorder, Serial No. 216717, manufactured by the Leeds and Northrup Company of Philadelphia, Pennsylvania. This instrument receives the thermocouple millivoltage, corrects it for cold junction temperature, and plots it on a time scale as a temperature. This instrument is capable of recording the temperature of three points in succession so the third set of terminals were shorted by a short copper wire and the room temperature or cold junction temperature was recorded in addition to the hot and cold face temperatures. The temperature readings are in degrees centigrade. See Figure IX.

The other hot and cold face temperatures are measured by taking millivolt readings of the thermocouple leads on a portable potentiometer Model 1117 manufactured by the Brown Instrument Company, Philadelphia, Pennsylvania. The millivolt readings taken by this instrument must be corrected for the cold junction temperature which was measured by a centigrade mercury-in-glass thermometer. Standard conversion tables of

millivolt readings to temperature in degrees centigrade or copper-constantan thermocouples were available for use.

The power input to the heating element was governed by the voltage applied to the terminals since the resistance of the element is constant. The voltage is controlled by a **variac** connected between the 110 V a.c. source and the heating element. The range of voltage available from the variac will produce a hot face temperature up to well over 100°C which is more than adequate for this work. The power input is measured by a Model 432 d-c and single phase a-c wattmeter, Serial No. 11588, manufactured by the Weston Electrical Instrument Corporation, Newark, New Jersey. An a.c. voltmeter Serial X8274 manufactured by the General Electric Co. of Schenectady, N. Y. was employed to check the wattmeter readings to determine whether the resistance of the heating element changed with temperature.

The sample box and insulating box were placed on the platform of a Model 98 Counting and Weighing machine Serial No. 98129 manufactured by the National Scale Company of Springfield, Massachusetts. The purpose of this feature was to facilitate weight measurements necessary to voids-ratio computations.

Instruments were used to aid in placement and compaction of these samples. One was a three pronged rodding instrument used for compaction of samples. The other was a screen that could be inserted in the sample

cavity and drawn upward during placement to obtain a very loose compaction.

U. S. Standard Sieves were used for grading the sand and determining the grading curve of the clay. A grinding machine Model F No. 4 manufactured by the Quaker City Mill Co. of Philadelphia, Pennsylvania was employed to grind the clay material.

Standard soil mechanics laboratory equipment was used to determined the desired physical properties necessary to the investigation.

See Figures VIIIa through VIIIf for the details of assembly of the equipment and orientation of measuring devices.

PART IV

PROCEDURE

PROCEDURE

The sample holder and insulating box were assembled as indicated in APPARATUS. The heater plate was positioned in the frame approximately midway between the edges, the spacer boards were inserted, and the cooling water jackets were lifted into position against the edges of the frame. The cooling jackets were then bolted against the frame, causing the spacer board to force the heater plate into its exact central position and causing the simple cavities to take on their accurate dimensions. Care was taken that the spacer boards fitted closely against the frame and that the thermocouple leads were hanging free. With the apparatus empty except for water flowing through the cooling jackets, with thermocouple leads hanging free and power leads not connected, an initial weight was determined.

The weighing procedure was intended to give the weight of sample directly from the difference between final and initial weights. All weighing was done with water flowing through the jackets and the power leads clear of the scales.

The original placement of the sample required extreme care in order to acquire uniformity of voids-ratio between the two sample sections, throughout each sample section, and to permit reproduction of

similar conditions in subsequent tests. The test material was poured into the sample cavity in small increment and, in order to obtain high voids-ratios, a 20" x 2" screen was drawn upward through the sample continuously during placement. The screen protected the loosely placed material below from disturbances caused by the act of placement. After exactly filling the front sample cavity the apparatus was weighed. The rear cavity was then filled in the same manner and the apparatus was again weighed. Comparison of these sample weights proved that this placement technique can give consistent results.

The insulating box cover was placed in position, the power leads were attached, and the variac was adjusted. Sufficient heating was obtained by using 150 watts for clay and 200 watts for sand samples.

The potentiometer-recorder was employed to indicate steady state conditions of heat flow. See Fig. IX. The repetition of the same temperature for five or six successive recordings with no trend toward a higher or lower reading was considered an accurate indication of equilibrium. The first test of a series was always performed on the sample of highest voids-ratio. Because the temperature of the material as placed

was essentially room temperature, more than twelve hours were allowed to attain equilibrium and a much longer succession of equal temperature readings was required in order to eliminate the possibility of a slight increasing or decreasing trend. When equilibrium was indicated, the recorder temperatures were read and the recorder was turned off. The millivolt readings of the thermocouples attached to the hot and cold faces of the other sample were then taken by use of the portable potentiometer. The reason the recorder was turned off was to eliminate vibration and electrical disturbance of the potentiometer during these readings by the recorder motor. See Fig. VIIIf.

The power to the heating element was then turned off, and the power leads were removed until the equipment was weighed to check the weight taken after placement. Then the top of the insulating box was removed and the power was again applied to the heating element to minimize the heat loss during compaction and addition of more material.

The sample was compacted a small amount in preparation for each successive test. This compaction was performed with the three pronged fork mentioned in Apparatus. Care was taken to maintain a uniform degree of compaction throughout each

sample section and between front and back cavities. The amount of settlement during the compaction process was maintained equal in each sample by using a like amount of compacting effort upon each. The sample sections were then filled completely by the addition of more of the material under test. Power to the heating element was turned off, and the weighing procedure was repeated. The leads were reconnected, and the power again was supplied to the heating plate. From one to two pounds of sample material were added after each compaction. The time required for compaction varied from fifteen to sixty minutes and the temperature of the hot face dropped only four to six degrees centigrade during the process.

Sufficient data was recorded for each test to be able to compute voids-ratio and thermal conductivity. The computation of voids-ratio made use of the formula

$$e = \frac{V_T \, G_s \, (1 + w)}{W_t} - 1 \qquad \ldots\ldots 5$$

where e = voids-ratio, i.e., volume of voids divided by volume of solids.

V_T = total volume of sample

G_s = true specific gravity of the sample

w = moisture content of the sample

W_t = total weight of the sample

The volume of the sample V_T remained constant because of the rigid construction of the sample box. The true specific gravity (G_s) of each sample was determined by other soil laboratory tests. The moisture content of each air-dried sample was taken before testing and the values were found to be of the order of .05% to .15% and were considered negligible. The total weight of each test sample was determined by subtraction of the initial weight from each intermediate weight.

Thermal conductivity was computed by the use of equation (2) $K = \frac{Qd}{t\ A\ (T_h - T_c)}$ where

Q/t = average power supplied to sample per unit of time.

d = average thickness of each sample in cm.

$T_h - T_c$ = average temperature difference between hot and cold faces.

The average power supplied to the sample per unit of time $\left(\frac{Q}{t}\right)$ after steady state flow had been attained was merely the wattmeter reading since equal amounts of heat entered and left the sample during equal time increments. The thickness of the sample (d) is held constant by the sample box design. The average temperature difference between the hot and cold faces of the sample ($T_h - T_c$) was determined from the potentiometer recorder and the portable potentiometer readings taken for each test.

As has been previously stated, the temperature of each face is given directly by the potentiometer recorder. The portable potentiometer reads the millivolt output of the thermocouples; and when corrected by the millivolt reading corresponding to the temperature of the instrument connection posts, the hot and cold face temperatures may be determined by the use of standard conversion tables for copper constantan thermocouples.

The use of average values of weight, power, and temperature difference served to minimize the effect of small variations in placement or instrument reading. To serve as additional checks against possible variations, especially against the possibility of disturbance of thermocouple installations during compaction, the thermocouple leads were often removed from the recorder posts and installed temporarily on the portable potentiometer along with the corresponding thermocouple normally read in that instrument. Discrepancies could be quickly noted by switching the instrument dial from one thermocouple to the other and noting any deflection of the needle. Quite often a difference of one or two millivolts was detected, but this small value was due to minor variations in compaction, and is considered well within experimental limits. The thermocouples themselves were calibrated for accuracy by immersing

the heater plate and cooling jackets in water. At successive water temperatures, the thermocouple readings were compared with the temperature of the water as measured by a mercury-in-glass thermometer. Extremely close agreement was observed throughout a range of 7°C to 65°C.

Each series of ten or more data runs was itself verified by a check series after the point of highest compaction had been obtained; the equipment was disassembled, and the sample was removed. The scales and surrounding floor area were carefully cleaned. The top and sides of the scale platform were shielded with paper to keep the sample from flowing under the scales. In this manner the sample material was kept free from contact with any foreign substance or dirt. After the sample box had been carefully cleaned of all sample, the check series was performed in exactly the same manner as described above. Because the number of check tests per series was usually much less than the number of original tests, a greater amount of compaction between check tests was used.

The aim of all techniques employed was to eliminate as much as possible the effects of uncontrollable variations and to provide subsequent investigators with a logical procedure which could produce consistent results.

PART V

RESULTS

RESULTS

The results of this investigation can most clearly be represented on a graph of the coefficient of thermal conductivity (K) vs. voids ratio (e) for each of the grain sizes tested.

Eleven data tests and three check tests were performed on the coarse sand size, 2.0 mm. - 0.42 mm. The average value of the coefficient of thermal conductivity (K) was .000869 cal/sec/cm/cm^2/°C. and the average value of voids-ratio (e) was .716. The results of these tests are tabulated in Table I, and are statistically analyzed in Table Ia. The graph of the results are shown on Figure I. Several points are considerably displaced from the resultant curve, but there seems to be little doubt that the variation is truly linear within the voids-ratio limits of the test.

Fourteen data tests and four check tests were performed on the medium sand size, 0.42 mm.-0.25 mm. The average value of (K) was found to be .000736 cal/sec/cm/cm^2/°C, and the average value of (e) was .842. The results of this series of tests as tabulated in Table II , are statistically analyzed in Table IIa, and are presented graphically in Figure II.

Eighteen data tests and five check tests were performed on the fine sand size, 0.25 mm. and lower.

The average value of (K) was found to be .000698 cal/sec/cm/cm^2/°C, and the average value of (e), 0.870. These results are tabulated, analyzed, and plotted in Tables III and IIIa, and Figure III, respectively.

It was noted that the average value of K decreased as the grain size of the sample decreased, that the average value of voids-ratio increased as the sample size decreased, and that for corresponding values of voids-ratio the coefficient of thermal conductivity decreased as the grain size decreased.

Values of thermal conductivity of sand determined for the different grain sizes were successively less than those values found by previous experimentors. Storch (1) found the average value of K to be .000962 cal/sec/cm/cm^2/°C. Hershel-LeBour and Dunn determined the value of the thermal conductivity of sand to be .00093 cal/sec/cm/cm^2/°C as given in the Handbook of Chemistry and Physics (8). Hogentogler (9) gives the values of K for dry white sand as .000932 cal/sec/cm/cm^2/°C. These experimentors dealt only with well-graded dry sand. The variation of K from the above values caused by grading and the variations between values of K for the different grain sizes at a representative voids-ratio of .75 are shown:

Grain Size	K cal/sec/cm/cm^2/°C
2.0 mm. ____ .42 mm.	.000845
.42 mm. ____ .25 mm.	.000779
.25 mm. ____ lower	.000761

When it is remembered that all previous investigations treat sand without regard to grain size classification, it does not seem that these data are inconsistent with other results. Each grain size tested showed the same close agreement with the linear variation between (K) and (e) mentioned above, within the voids-ratio limits of the test.

Thirteen data tests and three check tests were performed on a well-graded clay sample, see Figure VI. The average value of K for these tests was .000575 cal/sec/cm/cm^2/°C and the average value of voids-ratio was 1.347. The results are tabulated, analyzed, and plotted in Tables IV and IIIa, and Figure V, respectively. Because no previous work has been conducted or publication of results made for this type of clay sample, no values for comparison are available. Lees-Chorlton in the Handbook of Chemistry and Physics quotes a value of thermal conductivity (K) of .00033 cal/sec/cm/cm^2/°C for "dry soil", showing the indefinite character of most tabular values and serving further to indicate the need for specific results.

PART VI

CONCLUSIONS and RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

It has been stated earlier in this investigation that the apparatus used had been tested by its designer, Herbert Storch, and that his value of the coefficient of thermal conductivity has been compared with the values of other investigators. At the beginning of the work, it seemed logical and necessary to believe, therefore, that the apparatus would produce accurate and consistent results. The discrepancy of Storch's average value of K of .000962 (1) from that of .000932 given by others can be explained by the very fact that it is an average derived from a series of tests, ranging from a very loose to a very compact condition. This average compaction may or may not have been the same as the compaction used in other tests, and Storch's work, as well as this investigation, shows the extent to which the coefficient of thermal conductivity depends upon the degree of compaction.

Having established the fact that the apparatus could give accurate results, the task of proper and logical operation of the equipment was next undertaken. The apparatus consisted essentially of a sample box, measuring equipment, and power control. The power input was an independent variable and the selection of its value was studied. The hot face

temperature was to be kept below 100°C in order to retain the hygroscopic moisture in the sample. To minimize the number of variables, either the hot face temperature or the power input could have been maintained constant over a series of tests. The decision was made to use a constant input of power because the power was much easier to control. To determine whether the thermal conductivity would change as the hot face temperature changed, the first series of check tests was made with an increased power. The selected value of power was chosen as 220 watts because this power was judged to produce a broad range of values of temperature difference, keeping the hot face temperature well under 100°C and showing a distinct drop in hot face temperature with each compaction. The percentage of error which would have been caused by inaccurate temperature measurements was minimized by the use of higher values of hot face temperature.

The technique of operating the equipment was stated in Procedure. This differed from the technique employed by Storch in a manner designed to produce a much larger number of tests and thereby prevent experimental discrepancies from influencing and clouding the results. Operating difficulties also affected the technique of operation.

One major difference between the technique employed and that used previously was the practice of allowing the cooling water to continue its flow during the weighing and compaction of the sample between tests.

The basic reason for this procedure was to avoid disturbance of a free-flowing water system. The water jackets, though quite heavy, were constructed of weak material, and their protection was imperative. Nearly two weeks' time was consumed in efforts to locate and repair leaks in the cooling jackets, and minor leaks which caused delays appeared several times during the course of the work in spite of the precautions taken. The cause of leaks was the large force which could be produced by even a slight pressure on the 20" x 20" surface of the jackets. The light gage metal was easily pulled away from the 1/16" copper plate at the soldered joints. Pressure increases sufficient to produce this condition were caused by stoppages of flow from air binding or from the water hoses pinching. Several methods for filling the water jackets and starting flow were tried using extreme care, but none was consistently successful for establishing flow without dangerous bulging of the water jackets. The air could not be expelled completely from the

jackets during the filling process, and the jackets always became air bound to a certain extent. A satisfactory flow condition was established only by delicate adjustment of water supply.

Although this procedure was dictated as a safety measure, an immediate result was to allow a very greatly increased number of tests to be made. The accuracy of the weights obtained was immediately investigated, and it was found that when the desired rate of flow was maintained there was no variation in weight which could be determined within the limit of accuracy of the scales in use. While compacting the sample between tests with the insulating top removed and the cooling water flowing, there would have been a pronounced cooling of the sample. To prevent this cooling, the idea of applying power to the heater plate during the compaction was tried. The hot face temperature dropped only three to five degrees centigrade during the process and this method made possible the rapidity of testing that was realized. A total of seventy one tests were made during a period of about forty five working days. Allowing for delays caused by leaks, the testing rate was nearly two tests per day. The additional amount of data obtained seems to justify any possible loss of accuracy and

certainly would minimize the effect of any inaccurate reading. Weights were always taken at the beginning and end of each test as additional checks on accuracy.

The curves obtained from the data taken were not surprising. It is known that a soil sample of uniform grain size can not be compacted as much as a well graded sample, and it would be expected that a lower average value of thermal conductivity would result in the sample of uniform grain size. Experiment confirmed these expectations.

Definite trends were established by the data taken: the smaller the grain size, the lower was the thermal conductivity for the same voids-ratio. This result holds true over the limits of voids-ratio attainable in this investigation; and, since the voids-ratio values obtained cover nearly the maximum compaction obtainable by any method, it would appear safe to say that the general statement was true. However, it does not seem proper to extend the curves obtained to extreme theoretical values of voids-ratio and make any valid predictions.

Straight line variation was obtained between the variables (e) and K and the resultant curves were quite conclusive over the range of each series. The tendency to extend a straight line to

its axes as a basis for further conclusions is quite strong. Storch (1) used this method to predict the analysis of his sand by comparing the theoretical zero voids-ratio value of thermal conductivity obtained from extrapolating his results with the hand book value of thermal conductivity of quartz. If such an analysis were attempted from the curves obtained in this work, different indications for analysis of material would result from each of the three curves. The results of such application of the curves appear not to be reasonable; and, therefore, no similar attempts will be made.

There is significance in the fact that each of the curves obtained lies totally below the curve of the next larger particle size. It can be stated that the grain size controls the value of heat conductivity more than the total amount of voids present in the sample. The resistance to heat flow in the sample is made up of the resistance to heat flow present in each grain, the contact resistance at the given boundaries, and the heat insulating property of air spaces. If the insulating property of the air spaces contributed most of the heat resistance, the coefficient of thermal conductivity would be equal or nearly so for corresponding values of voids-ratio. Since

this result was not found experimentally, the other resistances to heat flow must predominate. The composition of the sample grains does not change from test to test, and the resistance to heat flow presented by the material of the grains should not change. The net length of the path of heat flow is the same in every test. The total length of the path of the heat flow varies between tests within each sample size depending upon the voids-ratio of the particular test. The length of this path should be similar in tests of two different particle sizes at the same voids-ratio; however, in the test upon the smaller particle size sample, this total length is composed of very many more individual grains than that path in the larger sample. From the results obtained herein, the conclusion is drawn that the contact resistance offers a major portion of the total resistance to heat flow, and that it is the principal cause of variation in thermal conductivity between the grain sizes tested.

A slightly different approach to the analysis of contact resistance to heat flow may be presented. During each series of tests when the material is compacted between tests, the positions of the grains were changed with respect to one another. When a well graded sample is under test, the voids are filled with the size of grain most closely

fitting each void. In a sample of uniform particle size, however, the grains are pushed together and change position to occupy a smaller space, not by occurying more suitable spaces but by assuming a contact surface with adjacent grains of a more close-fitting nature. The ultimate low value of voids-ratio is, of course, not as compact as that of a well-graded sample, but when it is reached the number of grain contacts is greater and the contact surface areas between grains are larger than in a lesser compaction. It is believed that these two factors are more responsible for an increasing value of the co-efficient of thermal conductivity than is the decreasing size of the air spaces during compaction. The void spaces are of such a small size that convection cannot be considered a contributing factor to heat flow, and, therefore, only the insulating property of air is effective in the tests conducted.

A composite graph of the curves obtained of each of the three sample sizes is shown in Figure IV. These curves illustrate the condition discussed above, as well as another trend. The material composed of the largest number of grain sizes seems to produce the greatest range of values of thermal conductivity. It is believed that this

increased range is caused by the more direct path of heat flow that would be the natural result of compaction of a better graded sample.

When the curve obtained by Storch is superimposed upon the composite graph, (Figure IV), a surprising condition results. The thermal conductivity is actually less for the well graded sample in high ranges of voids-ratio than the thermal conductivity of the coarse sand sample. This condition immediately suggests that for values of low voids-ratio the larger size grains are more effective in heat transmission, whereas with the sample in a loose condition the smaller size grains tend to govern the heat flow. The latter conclusion, however, is the result of background extrapolation of Storch's curve (shown dotted in Figure IV) and will not be assumed valid. What does seem to be indicated is that at high values of voids-ratio the heat transfer path in the well graded sample is across many more contact points than occur along that path through the coarse sand sample because the well graded sample contains many more grains of smaller sizes. On the other hand, when the lower voids-ratios are reached, the path of heat flow through the well graded sample is much more direct than the path through the sample of uniform grain size,

and the resultant conductivity is, therefore, greater.

The graph of coefficient of thermal conductivity of clay versus voids-ratio follows the trend already described for sand. In the case of clay, no comparison can be made with established values for the thermal conductivity because no established values exist. Further explanation of the reasons for an increasing conductivity with a decreasing voids-ratio need not be made. It is believed that the value of thermal conductivity obtained within the voids-ratio limits of the experiment are valid and the curve represented is conclusive. The lower value of thermal conductivity for clay than for sand must be caused by the flocculent structure of the clay particles themselves, as well as the high percentage of voids and the greatly increased number of contact points presented by the smaller particle size of the material.

The nature of the clay sample and the compaction equipment available, limited the degree of compaction obtained. The clay sample was clean, natural clay taken from deposits in Watervliet, New York, dried and ground in the soil grinding mill referred to in Apparatus. The clay sizes obtained from grinding varied from sizes

[illegible]

[illegible]

[illegible]

passing a No. 10 sieve to fine sizes of .009 mm. and smaller. A smaller maximum size could have been obtained, but would have required an excessive amount of grinding time. The percentage of particle sizes above a 200 mesh sieve appears small in the grading curve of clay, Figure VI, but the standard laboratory procedure for obtaining this curve causes wetting and division of natural particle groups. As actually used, the sample contained about 8% by weight of clay lumps which would not pass a 200 mesh sieve.

The minimum void ratio attainable by the compaction equipment used was 1.035. This definitely appears high, but was obtained only after more than an hour's time spent in rodding the sample with both the three pronged fork and a wooden board. Even pounding the board with a heavy mallet was employed. It is advised that a better technique for clay compaction be sought for subsequent work involving a greater number of clay tests.

Subsequent work on the thermal conductivity of soil samples will deal more searchingly with clay, and also investigate the effect of moisture in soils. The samples used in this work were air dry with moisture contents varying from .05% to .14% before testing and from .04% to

.09% after testing. This minor amount of moisture was considered to be negligible in this work, and a true measurement of the moisture content in the sample during a series of tests would have been impossible. In the work to be done it is possible that the measurement of thermal conductivity of completely saturated soil will be undertaken. This work would be impossible with the apparatus in its present form and using the techniques hitherto established.

The equipment is composed largely of wood. The sample is in direct contact with the wooden spacer boards, and no water tight seal exists between the sample and the insulation box. In ordinary work with dry samples, leaks in the cooling jackets caused water to soak into the wood of the insulating box. Change in the weight of the wooden box of as much as one pound was noted. Another effect of water seepage with the insulating box would be to decrease the effectiveness of the insulation. Thus, it can be seen that a water tight sample compartment is essential to subsequent work.

Two means of obtaining this condition have been considered. The first method is to waterproof the spacer boards with paraffin, cut rubber gaskets to seal the spacer boards against the hot and cold

face plates, and cover the top of the sample with a gasket held in place by the insulating box cover.

A second method of water proofing the sample container is to fabricate a light gage metal box with reinforced edges and bottom which could be inserted into the sample cavities. The thermocouple locations could be changed to the faces of these boxes and the weight of the soil would press the sides of the boxes against the existing hot and cold faces. This type of container could be fitted with a gasketed lid and lifting handles to make it a completely water tight, removable container. The removable element of the proposed boxes would save in time consumed in changing samples and in the wear imposed on the sample holder frame and insulating box resulting from repeated assembly and break-down.

A method for maintaining a uniform distribution of a given water content in a sample has not been devised. An agitation of the sample during testing to prevent excessive moisture migration from the hot face would seem to be necessary. Such agitation would, however, change the voids-ratio of the sample, intermingle hot and cold soil, and destroy established paths of heat flow. A careful study of this requirement should be made along with the water

tightness requirements already discussed. The conclusion might possibly be reached which precludes the use of equipment in even its basic present form. It is well to note here that the process of calibrating thermocouples, see Procedure, also yielded the information that the heater plate could satisfactorily be used with the elements in a damp condition. The element was dried after immersion by the application of 450 watts of power with no detrimental effects. It is advised, however, that if the equipment is to be used in its present form the cooling jackets be completely disassembled and refabricated, using brazed joints instead of soldered joints. It would also be advisable to install petcocks on the tops of the jackets to serve as air releases.

During the experiments conducted upon the dry sand samples, moisture migration was noted to occur from the hot face to the cold face of the equipment. It must be remembered that the moisture content of the soil was less than one half of one percent. On days when the atmospheric relative humidity was not large enough to cause condensation upon the room face of the cooling jackets, this condition of moisture migration was in evidence.

The fact is established, therefore, that the moisture which migrated did come from the hygroscopic

moisture of the sand itself and not from the atmosphere. To complete the experimental verification of the theory of thermo-osmosis, there need only be demonstrated that the migration was the result of the temperature difference between the hot and cold faces. When the power to the heating element was secured, it took only four to six hours for the moisture which had migrated to the cold face to disappear into the remainder of the sample mass. The migration did again appear soon after the power was reapplied.

When the equipment was disassembled between test series while the heater plate was still hot, the cold faces of the equipment exhibited a layer of moist sand adhering to them. This layer was held in place by a strong bond of capillarity and the thickness of the layer was greater for the fine sand sample. These observations do strongly tend to substantiate the thermo-osmotic theory.

The limitations of the equipment itself confine the discussion of thermo-osmosis to a mere observation of the phenomenon. Subsequent work in this field will require further modification of the equipment to enable measurement of the thickness of the adhering layer and of other as yet unknown variables. It is suggested that,

if the light gage metal box method is employed, a hinged side be incorporated into the design to provide a means of exposing the full face exhibiting the migration layer with the least amount of disturbance by the remainder of the sample.

The migration was observed to be the greatest in the particle size most suitable to strong capillary action. The significance of the phenomenon displayed is that another means for supplying water causing frost heave is now shown The surface of the ground would in this case act as a cold face, and the subsurface would act not only as a source of water for capillary flow, but also as a hot face which would accelerate the normal capillary flow as a result of thermo-osmosis.

PART VII

APPENDIX

THERMAL CONDUCTIVITY TEST

Date March 7, 1950

Test No. 101

MATERIAL/SIZE: Cow Bay Sand 2.0 to .42 mm.

Wt. Test Box 195.0
Wt. Test Box & Samples 279.0
Wt. 2 Samples 84.0

Total Power 167.0
Average Power 83.5
Average Wt. Sample 42.0

POTENTIOMETER:

Ref. Junc. Temp. 17.3 °C = .68 mv
Hot Face Corr. Read. 2.38 mv = 58 °C
Cold Face Corr. Read. .19 mv = 5 °C
Temp. Diff. 53

RECORDER:

Hot Face Temp. 59 °C
Cold Face Temp. 6 °C
Temp Diff. 53
Ave. Temp. Diff. 53

Date March 8 1950

Test No. 102

MATERIAL/SIZE: As Above

Wt. Test Box 195.0
Wt. Test Box & Samples 280.5
Wt. 2 Samples 85.5

Total Power 220
Average Power 110
Average Wt. Sample 42.7

POTENTIOMETER:

Ref. Junc. Temp. 18.7 °C = .74 mv
Hot Face Corr. Read. 2.95 mv = 71 °C
Cold Face Corr. Read. .21 mv = 5.5 °C
Temp. Diff. 65.5

RECORDER:

Hot Face Temp. 73 °C
Cold Face Temp. 8 °C
Temp Diff. 65
Ave. Temp. Diff. 65.25

THERMAL CONDUCTIVITY TEST

Date *March 9*, 1950

Test No. 103

MATERIAL/SIZE: *Cow Bay Sand* *2.0 to .42 mm.*

Wt. Test Box	195.0	Total Power	220
Wt. Test Box & Samples	281.8	Average Power	110
Wt. 2 Samples	86.8	Average Wt. Sample	43.4

POTENTIOMETER:

Ref. Junc. Temp.	15.8 °C =	.62 mv	Temp.	
Hot Face Corr. Read.	2.82 mv =	68 °C	Diff.	62
Cold Face Corr. Read.	.22 mv =	6 °C		

RECORDER:

Hot Face Temp.	70 °C	Temp Diff.	62
Cold Face Temp.	8 °C	Ave. Temp. Diff.	62

Date *March 9*, 1950

Test No. 104

MATERIAL/SIZE: *As Above*

Wt. Test Box	195.0	Total Power	212
Wt. Test Box & Samples	282.6	Average Power	106
Wt. 2 Samples	87.6	Average Wt. Sample	43.8

POTENTIOMETER:

Ref. Junc. Temp.	17.0 °C =	.67 mv	Temp.	
Hot Face Corr. Read.	2.74 mv =	66.2 °C	Diff.	59.95
Cold Face Corr. Read.	.24 mv =	6.25 °C		

RECORDER:

Hot Face Temp.	67.5 °C	Temp Diff.	59.5
Cold Face Temp.	8 °C	Ave. Temp. Diff.	59.72

THERMAL CONDUCTIVITY TEST

Date March 10, 1950

Test No. 105

MATERIAL/SIZE: Cow Bay Sand 2.0 to .42 mm.

Wt. Test Box 195.0
Wt. Test Box & Samples 283.8
Wt. 2 Samples 88.8

Total Power 222
Average Power 111
Average Wt. Sample 44.4

POTENTIOMETER:

Ref. Junc. Temp. 19.0 °C = .75 mv
Hot Face Corr. Read. 2.70 mv = 65.25 °C
Cold Face Corr. Read. .22 mv = 5.75 °C

Temp. Diff. 59.5

RECORDER:

Hot Face Temp. 67 °C
Cold Face Temp. 8 °C

Temp Diff. 59
Ave. Temp. Diff. 59.25

Date March 10, 1950

Test No. 106

MATERIAL/SIZE: As Above

Wt. Test Box 195.0
Wt. Test Box & Samples 284.8
Wt. 2 Samples 89.8

Total Power 225
Average Power 112.5
Average Wt. Sample 44.9

POTENTIOMETER:

Ref. Junc. Temp. 19.0 °C = .75 mv
Hot Face Corr. Read. 2.59 mv = 62.75 °C
Cold Face Corr. Read. .23 mv = 6.00 °C

Temp. Diff. 56.75

RECORDER:

Hot Face Temp. 64 °C
Cold Face Temp. 8 °C

Temp Diff. 56
Ave. Temp. Diff. 56.38

THERMAL CONDUCTIVITY TEST

Date *March 11*, 1950

Test No. *107*

MATERIAL/SIZE: *Cow Bay Sand* *2.0 to .42 mm.*

Wt. Test Box *195.0*
Wt. Test Box & Samples *285.7*
Wt. 2 Samples *90.7*

Total Power *220*
Average Power *110*
Average Wt. Sample *45.35*

POTENTIOMETER:

Ref. Junc. Temp. *22.6* °C = *.89* mv
Hot Face Corr. Read. *2.69* mv = *65.00* °C
Cold Face Corr. Read. *.26* mv = *6.75* °C

Temp. Diff. *58.25*

RECORDER:

Hot Face Temp. *66.0* °C
Cold Face Temp. *8.0* °C

Temp Diff. *58.0*
Ave. Temp. Diff. *58.12*

Date *March 11*, 1950

Test No. *108*

MATERIAL/SIZE: *As Before*

Wt. Test Box *195.0*
Wt. Test Box & Samples *286.6*
Wt. 2 Samples *91.6*

Total Power *220*
Average Power *110*
Average Wt. Sample *45.8*

POTENTIOMETER:

Ref. Junc. Temp. *23.0* °C = *.91* mv
Hot Face Corr. Read. *2.68* mv = *65.0* °C
Cold Face Corr. Read. *.27* mv = *7.0* °C

Temp. Diff. *58*

RECORDER:

Hot Face Temp. *66* °C
Cold Face Temp. *9* °C

Temp Diff. *57*
Ave. Temp. Diff. *57.5*

THERMAL CONDUCTIVITY TEST

Date *March 12*, 1950

Test No. 109

MATERIAL/SIZE: *Cow Bay Sand* 2.0 to .42 mm.

Wt. Test Box 195.0
Wt. Test Box & Samples 287.6
Wt. 2 Samples 92.6

Total Power 215
Average Power 107.5
Average Wt. Sample 46.3

POTENTIOMETER:

Ref. Junc. Temp. 19.3 °C = .76 mv
Hot Face Corr. Read. 2.54 mv = 61.6 °C
Cold Face Corr. Read. .25 mv = 6.5 °C
Temp. Diff. 55.1

RECORDER:

Hot Face Temp. 64 °C
Cold Face Temp. 9 °C
Temp Diff. 55
Ave. Temp. Diff. 55.05

Date *March 12*, 1950

Test No. 110

MATERIAL/SIZE: *As Above*

Wt. Test Box 195.0
Wt. Test Box & Samples 289.0
Wt. 2 Samples 94.0

Total Power 218
Average Power 109
Average Wt. Sample 47.0

POTENTIOMETER:

Ref. Junc. Temp. 22 °C = .87 mv
Hot Face Corr. Read. 2.56 mv = 62 °C
Cold Face Corr. Read. .27 mv = 7 °C
Temp. Diff. 55

RECORDER:

Hot Face Temp. 63 °C
Cold Face Temp. 8 °C
Temp Diff. 55
Ave. Temp. Diff. 55.0

THERMAL CONDUCTIVITY TEST

Date *March 13,* 1950

Test No. 111

MATERIAL/SIZE: *Cow Bay Sand* *2.0 to .42 mm.*

Wt. Test Box 195.0 Total Power 220
Wt. Test Box & Samples 292.3 Average Power 110
Wt. 2 Samples 97.3 Average Wt. Sample 48.7

POTENTIOMETER:

Ref. Junc. Temp. 21 °C = .83 mv Temp.
Hot Face Corr. Read. 2.33 mv = 57 °C Diff. 52
Cold Face Corr. Read. .19 mv = 5 °C

RECORDER:

Hot Face Temp. 61 °C Temp Diff. 52
Cold Face Temp. 9 °C Ave. Temp. Diff. 52.0

Date *March 14,* 1950

Test No. 1-B

MATERIAL/SIZE: *As Above*

Wt. Test Box 195.0 Total Power 250
Wt. Test Box & Samples 280.4 Average Power 125
Wt. 2 Samples 85.4 Average Wt. Sample 42.7

POTENTIOMETER:

Ref. Junc. Temp. 20.7 °C = .82 mv Temp.
Hot Face Corr. Read. 3.28 mv = 78.25 °C Diff. 71
Cold Face Corr. Read. .28 mv = 7.25 °C

RECORDER:

Hot Face Temp. 79 °C Temp Diff. 71
Cold Face Temp. 8 °C Ave. Temp. Diff. 71

THERMAL CONDUCTIVITY TEST

Date *March 15,* 1950

Test No. 1-B

MATERIAL/SIZE: *Cow Bay Sand 2.0 to .42 mm.*

Wt. Test Box 195.0
Wt. Test Box & Samples 284.5
Wt. 2 Samples 89.5

Total Power 250
Average Power 125
Average Wt. Sample 44.75

POTENTIOMETER:

Ref. Junc. Temp. 20.4 °C = .81 mv
Hot Face Corr. Read. 3.08 mv = 73.8 °C
Cold Face Corr. Read. .27 mv = 7 °C
Temp. Diff. 66.8

RECORDER:

Hot Face Temp. 75 °C Temp Diff. 66.75
Cold Face Temp. 8.25 °C Ave. Temp. Diff. 66.8

Date *March 15,* 1950

Test No. 1-C

MATERIAL/SIZE: *As Above*

Wt. Test Box 195.0
Wt. Test Box & Samples 288.8
Wt. 2 Samples 93.8

Total Power 250
Average Power 125
Average Wt. Sample 46.9

POTENTIOMETER:

Ref. Junc. Temp. 21.7 °C = .86 mv
Hot Face Corr. Read. 2.92 mv = 70.25 °C
Cold Face Corr. Read. .28 mv = 7.25 °C
Temp. Diff. 63

RECORDER:

Hot Face Temp. 72 °C Temp Diff. 63
Cold Face Temp. 9 °C Ave. Temp. Diff. 63

THERMAL CONDUCTIVITY TEST

Date MAR 17 1950

Test No. 201

MATERIAL/SIZE: Cow Bay Sand .42-.25 MM

Wt. Test Box 195.9 Total Power 220
Wt. Test Box & Samples 274.3 Average Power 110
Wt. 2 Samples 78.4 Average Wt. Sample 39.2

POTENTIOMETER:

Ref. Junc. Temp. 22.3 °C = .88 mv
Hot Face Corr. Read. 3.38 mv = 80.5 °C Temp. Diff. 74.25
Cold Face Corr. Read. .24 mv = 6.25 °C

RECORDER:

Hot Face Temp. 82.2 °C Temp Diff. 73.2
Cold Face Temp. 9.0 °C Ave. Temp. Diff. 73.72

Date MAR 18 1950

Test No. 202

MATERIAL/SIZE: As Above

Wt. Test Box 195.9 Total Power 220
Wt. Test Box & Samples 277.7 Average Power 110
Wt. 2 Samples 81.8 Average Wt. Sample 40.9

POTENTIOMETER:

Ref. Junc. Temp. 22.2 °C = .88 mv
Hot Face Corr. Read. 3.40 mv = 81.0 °C Temp. Diff. 74.0
Cold Face Corr. Read. .27 mv = 7.0 °C

RECORDER:

Hot Face Temp. 80.0 °C Temp Diff. 72.0
Cold Face Temp. 8.0 °C Ave. Temp. Diff. 73.0

THERMAL CONDUCTIVITY TEST

Date MAR 19 1950

Test No. 203

MATERIAL/SIZE: Cow Bay Sand .42 -.25 mm

Wt. Test Box 195.9
Wt. Test Box & Samples 279.7
Wt. 2 Samples 83.8

Total Power 220
Average Power 110
Average Wt. Sample 41.9

POTENTIOMETER:

Ref. Junc. Temp. 21.0 °C = .83 mv
Hot Face Corr. Read. 3.25 mv = 77.6 °C
Cold Face Corr. Read. .28 mv = 7.25 °C
Temp. Diff. 70.35

RECORDER:

Hot Face Temp. 78.4 °C
Cold Face Temp. 8.0 °C
Temp Diff. 70.4
Ave. Temp. Diff. 70.37

Date MAR 19 1950

Test No. 204

MATERIAL/SIZE: As Above

Wt. Test Box 195.9
Wt. Test Box & Samples 280.8
Wt. 2 Samples 84.9

Total Power 220
Average Power 110
Average Wt. Sample 42.45

POTENTIOMETER:

Ref. Junc. Temp. 23.2 °C = .92 mv
Hot Face Corr. Read. 3.26 mv = 77.8 °C
Cold Face Corr. Read. .32 mv = 8.25 °C
Temp. Diff. 69.55

RECORDER:

Hot Face Temp. 77.0 °C
Cold Face Temp. 8.0 °C
Temp Diff. 69.0
Ave. Temp. Diff. 69.28

THERMAL CONDUCTIVITY TEST

Date *Mar 20* 1950

Test No. *205*

MATERIAL/SIZE: *Cow Bay Sand .42 -.25 mm*

Wt. Test Box *195.9* Total Power *220*
Wt. Test Box & Samples *282.2* Average Power *110*
Wt. 2 Samples *86.3* Average Wt. Sample *43.15*

POTENTIOMETER:

Ref. Junc. Temp. *23.2* °C = *.91* mv Temp.
Hot Face Corr. Read. *3.13* mv = *75.0* °C Diff. *67.5*
Cold Face Corr. Read. *.29* mv = *7.5* °C

RECORDER:

Hot Face Temp. *75.0* °C Temp Diff. *67*
Cold Face Temp. *8.0* °C Ave. Temp. Diff. *67.25*

Date *Mar 20* 1950

Test No. *206*

MATERIAL/SIZE: *As Above*

Wt. Test Box *195.9* Total Power *220*
Wt. Test Box & Samples *283.7* Average Power *110*
Wt. 2 Samples *87.8* Average Wt. Sample *43.9*

POTENTIOMETER:

Ref. Junc. Temp. *24* °C = *.95* mv Temp.
Hot Face Corr. Read. *3.09* mv = *74.0* °C Diff. *66.0*
Cold Face Corr. Read. *.31* mv = *8.0* °C

RECORDER:

Hot Face Temp. *74.0* °C Temp Diff. *65*
Cold Face Temp. *9.0* °C Ave. Temp. Diff. *65.5*

THERMAL CONDUCTIVITY TEST

Date MAR 21 1950

Test No. 207

MATERIAL/SIZE: Cow Bay Sand .42-.25 mm

Wt. Test Box 195.9 Total Power 228
Wt. Test Box & Samples 285.4 Average Power 114
Wt. 2 Samples 89.5 Average Wt. Sample 44.75

POTENTIOMETER:

Ref. Junc. Temp. 22.8 °C = .90 mv Temp.
Hot Face Corr. Read. 3.10 mv = 74.25 °C Diff. 66.25
Cold Face Corr. Read. .31 mv = 8.00 °C

RECORDER:

Hot Face Temp. 74.5 °C Temp Diff. 66.25
Cold Face Temp. 8.25 °C Ave. Temp. Diff. 66.25

Date MAR 25 1950

Test No. 251

MATERIAL/SIZE: As Above

Wt. Test Box 194.5 Total Power 210
Wt. Test Box & Samples 273.9 Average Power 105
Wt. 2 Samples 79.4 Average Wt. Sample 39.7

POTENTIOMETER:

Ref. Junc. Temp. 22.0 °C = .87 mv Temp.
Hot Face Corr. Read. 3.46 mv = 82.2 °C Diff. 73.95
Cold Face Corr. Read. .32 mv = 8.25 °C

RECORDER:

Hot Face Temp. 84 °C Temp Diff. 74.4
Cold Face Temp. 9.6 °C Ave. Temp. Diff. 74.18

THERMAL CONDUCTIVITY TEST

Date Mar 26 1950

Test No. 252

MATERIAL/SIZE: Cow Bay Sand .42 -.25 mm

Wt. Test Box 194.5
Wt. Test Box & Samples 275.0
Wt. 2 Samples 80.5

Total Power 220
Average Power 110
Average Wt. Sample 40.25

POTENTIOMETER:

Ref. Junc. Temp. 22.3 °C = .88 mv
Hot Face Corr. Read. 3.40 mv = 81.0 °C
Cold Face Corr. Read. .28 mv = 7.25 °C
Temp. Diff. 73.75

RECORDER:

Hot Face Temp. 82.0 °C
Cold Face Temp. 8.2 °C
Temp Diff. 73.8
Ave. Temp. Diff. 73.78

Date Mar 27 1950

Test No. 253

MATERIAL/SIZE: As Above

Wt. Test Box 194.5
Wt. Test Box & Samples 276.6
Wt. 2 Samples 82.1

Total Power 228
Average Power 114
Average Wt. Sample 41.05

POTENTIOMETER:

Ref. Junc. Temp. 21.2 °C = .84 mv
Hot Face Corr. Read. 3.51 mv = 83.5 °C
Cold Face Corr. Read. .32 mv = 8.25 °C
Temp. Diff. 75.25

RECORDER:

Hot Face Temp. 84.4 °C
Cold Face Temp. 8.2 °C
Temp Diff. 76.2
Ave. Temp. Diff. 75.72

THERMAL CONDUCTIVITY TEST

Date *Mar 28* 1950

Test No. *254*

MATERIAL/SIZE: *Cow Bay Sand .42 - .25 mm*

Wt. Test Box *194.5*
Wt. Test Box & Samples *277.5*
Wt. 2 Samples *83.0*

Total Power *220*
Average Power *110*
Average Wt. Sample *41.5*

POTENTIOMETER:

Ref. Junc. Temp. *18.0* °C = *.71* mv
Hot Face Corr. Read. *3.38* mv = *80.5* °C
Cold Face Corr. Read. *.32* mv = *8.25* °C
Temp. Diff. *72.25*

RECORDER:

Hot Face Temp. *81.2* °C Temp Diff. *71.6*
Cold Face Temp. *9.6* °C Ave. Temp. Diff. *71.92*

Date *Mar 28* 1950

Test No. *255*

MATERIAL/SIZE: *As Above*

Wt. Test Box *194.5*
Wt. Test Box & Samples *279.0*
Wt. 2 Samples *84.5*

Total Power *220*
Average Power *110*
Average Wt. Sample *42.25*

POTENTIOMETER:

Ref. Junc. Temp. *19.3* °C = *.76* mv
Hot Face Corr. Read. *3.26* mv = *77.8* °C
Cold Face Corr. Read. *.29* mv = *7.5* °C
Temp. Diff. *70.3*

RECORDER:

Hot Face Temp. *79.4* °C Temp Diff. *69.6*
Cold Face Temp. *9.8* °C Ave. Temp. Diff. *69.95*

THERMAL CONDUCTIVITY TEST

Date *Mar 29* 1950

Test No. *256*

MATERIAL/SIZE: *Cow Bay Sand .42-.25 mm*

Wt. Test Box *194.5*
Wt. Test Box & Samples *281.8*
Wt. 2 Samples *87.3*

Total Power *227.5*
Average Power *114*
Average Wt. Sample *43.65*

POTENTIOMETER:

Ref. Junc. Temp. *19.6* °C = *.77* mv
Hot Face Corr. Read. *3.19* mv = *76.25* °C
Cold Face Corr. Read. *.34* mv = *8.75* °C
Temp. Diff. *67.5*

RECORDER:

Hot Face Temp. *77.9* °C
Cold Face Temp. *10.1* °C
Temp Diff. *67.8*
Ave. Temp. Diff. *67.65*

Date *Mar 29* 1950

Test No. *257*

MATERIAL/SIZE: *As Above*

Wt. Test Box *194.5*
Wt. Test Box & Samples *285.5*
Wt. 2 Samples *91.0*

Total Power *227*
Average Power *113.5*
Average Wt. Sample *45.5*

POTENTIOMETER:

Ref. Junc. Temp. *21.0* °C = *.83* mv
Hot Face Corr. Read. *3.12* mv = *74.75* °C
Cold Face Corr. Read. *.35* mv = *9.00* °C
Temp. Diff. *65.75*

RECORDER:

Hot Face Temp. *75.9* °C
Cold Face Temp. *10.1* °C
Temp Diff. *65.8*
Ave. Temp. Diff. *65.78*

THERMAL CONDUCTIVITY TEST

Date MAR 22 1950

Test No. 2-A

MATERIAL/SIZE: Cow Bay Sand - .42-.25 mm

Wt. Test Box 197.7
Wt. Test Box & Samples 276.6
Wt. 2 Samples 78.9

Total Power 220
Average Power 110
Average Wt. Sample 39.45

POTENTIOMETER:

Ref. Junc. Temp. 22.0 °C = .87 mv
Hot Face Corr. Read. 3.37 mv = 80.25 °C
Cold Face Corr. Read. .34 mv = 8.75 °C
Temp. Diff. 71.5

RECORDER:

Hot Face Temp. 79.5 °C
Cold Face Temp. 8.25 °C
Temp Diff. 71.25
Ave. Temp. Diff. 71.38

Date MAR 23 1950

Test No. 2-B

MATERIAL/SIZE: As Above

Wt. Test Box 197.7
Wt. Test Box & Samples 277.6
Wt. 2 Samples 79.9

Total Power 215
Average Power 107.5
Average Wt. Sample 39.95

POTENTIOMETER:

Ref. Junc. Temp. 20.7 °C = .82 mv
Hot Face Corr. Read. 3.31 mv = 79.0 °C
Cold Face Corr. Read. .23 mv = 6.0 °C
Temp. Diff. 73.0

RECORDER:

Hot Face Temp. 81.0 °C
Cold Face Temp. 9.5 °C
Temp Diff. 71.5
Ave. Temp. Diff. 72.25

THERMAL CONDUCTIVITY TEST

Date MAR 23 1950

Test No. 2-C

MATERIAL/SIZE: Cow Bay Sand .42-.25 mm

Wt. Test Box 197.7
Wt. Test Box & Samples 281.9
Wt. 2 Samples 84.2

Total Power 212
Average Power 106
Average Wt. Sample 42.1

POTENTIOMETER:

Ref. Junc. Temp. 23.6 °C = .93 mv
Hot Face Corr. Read. 3.17 mv = 75.8 °C
Cold Face Corr. Read. .36 mv = 9.25 °C
Temp. Diff. 66.55

RECORDER:

Hot Face Temp. 73.9 °C
Cold Face Temp. 10.0 °C
Temp Diff. 63.9
Ave. Temp. Diff. 65.22

Date MAR 24 1950

Test No. 2-D

MATERIAL/SIZE: As Above

Wt. Test Box 197.7
Wt. Test Box & Samples 287.8
Wt. 2 Samples 90.1

Total Power 225
Average Power 112.5
Average Wt. Sample 45.05

POTENTIOMETER:

Ref. Junc. Temp. 25.0 °C = .99 mv
Hot Face Corr. Read. 3.11 mv = 74.5 °C
Cold Face Corr. Read. .35 mv = 9.0 °C
Temp. Diff. 65.5

RECORDER:

Hot Face Temp. 71.5 °C
Cold Face Temp. 9.5 °C
Temp Diff. 62.0
Ave. Temp. Diff. 63.75

THERMAL CONDUCTIVITY TEST

Date April 14, 1950

Test No. 301

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box	194.5	Total Power	220
Wt. Test Box & Samples	271.1	Average Power	110
Wt. 2 Samples	76.6	Average Wt. Sample	38.3

POTENTIOMETER:

Ref. Junc. Temp.	21 °C	=	.83 mv	Temp.	
Hot Face Corr. Read.	3.78 mv	=	89.25 °C	Diff.	80.25
Cold Face Corr. Read.	.35 mv	=	9.0 °C		

RECORDER:

Hot Face Temp.	90.3 °C	Temp Diff.	80.3
Cold Face Temp.	10 °C	Ave. Temp. Diff.	80.28

Date April 15, 1950

Test No. 302

MATERIAL/SIZE: As Above

Wt. Test Box	194.5	Total Power	220
Wt. Test Box & Samples	272.2	Average Power	110
Wt. 2 Samples	77.7	Average Wt. Sample	38.6

POTENTIOMETER:

Ref. Junc. Temp.	23 °C	=	.91 mv	Temp.	
Hot Face Corr. Read.	3.65 mv	=	86.50 °C	Diff.	76.75
Cold Face Corr. Read.	.38 mv	=	9.75 °C		

RECORDER:

Hot Face Temp.	88 °C	Temp Diff.	78
Cold Face Temp.	10 °C	Ave. Temp. Diff.	77.38

THERMAL CONDUCTIVITY TEST

Date *April 16,* 1950

Test No. 303

MATERIAL/SIZE: *Cow Bay Sand* .25 mm., lower

Wt. Test Box 194.5
Wt. Test Box & Samples 273.0
Wt. 2 Samples 78.5

Total Power 220
Average Power 110
Average Wt. Sample 39.2

POTENTIOMETER:

Ref. Junc. Temp. 20 °C = .79 mv
Hot Face Corr. Read. 3.83 mv = 90.4 °C
Cold Face Corr. Read. .39 mv = 10 °C

Temp. Diff. 80.4

RECORDER:

Hot Face Temp. 91.7 °C
Cold Face Temp. 11.3 °C
Temp Diff. 80.4
Ave. Temp. Diff. 80.4

Date *April 17,* 1950

Test No. 304

MATERIAL/SIZE: *As Above*

Wt. Test Box 194.5
Wt. Test Box & Samples 273.5
Wt. 2 Samples 79.0

Total Power 220
Average Power 110
Average Wt. Sample 39.5

POTENTIOMETER:

Ref. Junc. Temp. 22.2 °C = .88 mv
Hot Face Corr. Read. 3.64 mv = 87.4 °C
Cold Face Corr. Read. .34 mv = 8.75 °C

Temp. Diff. 78.65

RECORDER:

Hot Face Temp. 90 °C
Cold Face Temp. 11 °C
Temp Diff. 79
Ave. Temp. Diff. 78.82

THERMAL CONDUCTIVITY TEST

Date *April 17*, 1950

Test No. 305

MATERIAL/SIZE: *Cow Bay Sand .25mm., lower*

Wt. Test Box	194.5	Total Power	222
Wt. Test Box & Samples	274.8	Average Power	111
Wt. 2 Samples	80.3	Average Wt. Sample	40.1

POTENTIOMETER:

Ref. Junc. Temp.	19.8 °C =	.77 mv	Temp. Diff. 78.55
Hot Face Corr. Read.	3.71 mv =	87.8 °C	
Cold Face Corr. Read.	.36 mv =	9.25 °C	

RECORDER:

Hot Face Temp.	90 °C	Temp Diff.	78.5
Cold Face Temp.	11.5 °C	Ave. Temp. Diff.	78.52

Date *April 18*, 1950

Test No. 306

MATERIAL/SIZE: *As Above*

Wt. Test Box	194.5	Total Power	230
Wt. Test Box & Samples	275.5	Average Power	115
Wt. 2 Samples	81.0	Average Wt. Sample	40.5

POTENTIOMETER:

Ref. Junc. Temp.	23 °C =	.91 mv	Temp. Diff. 78.5
Hot Face Corr. Read.	3.81 mv =	90 °C	
Cold Face Corr. Read.	.45 mv =	11.5 °C	

RECORDER:

Hot Face Temp.	91.5 °C	Temp Diff.	79.9
Cold Face Temp.	11.6 °C	Ave. Temp. Diff.	79.2

THERMAL CONDUCTIVITY TEST

Date April 18, 1950

Test No. 307

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box 194.5
Wt. Test Box & Samples 276.6
Wt. 2 Samples 82.1

Total Power 227
Average Power 113.5
Average Wt. Sample 41.0

POTENTIOMETER:

Ref. Junc. Temp. 19.3 °C = .76 mv
Hot Face Corr. Read. 3.78 mv = 89.25 °C
Cold Face Corr. Read. .36 mv = 9.25 °C
Temp. Diff. 80

RECORDER:

Hot Face Temp. 91.5 °C
Cold Face Temp. 11.8 °C
Temp Diff. 79.7
Ave. Temp. Diff. 79.85

Date April 19, 1950

Test No. 308

MATERIAL/SIZE: As Above

Wt. Test Box 194.5
Wt. Test Box & Samples 276.7
Wt. 2 Samples 82.2

Total Power 220
Average Power 110
Average Wt. Sample 41.1

POTENTIOMETER:

Ref. Junc. Temp. 24.6 °C = .97 mv
Hot Face Corr. Read. 3.66 mv = 86.75 °C
Cold Face Corr. Read. .47 mv = 12 °C
Temp. Diff. 74.75

RECORDER:

Hot Face Temp. 88.1 °C
Cold Face Temp. 11.4 °C
Temp Diff. 76.7
Ave. Temp. Diff. 75.72

THERMAL CONDUCTIVITY TEST

Date April 19, 1950

Test No. 309

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box	194.5	Total Power	220
Wt. Test Box & Samples	277.9	Average Power	110
Wt. 2 Samples	83.4	Average Wt. Sample	41.7

POTENTIOMETER:

Ref. Junc. Temp. 20.8 °C = .82 mv
Hot Face Corr. Read. 3.54 mv = 84.0 °C
Cold Face Corr. Read. .36 mv = 9.25 °C
Temp. Diff. 74.75

RECORDER:

Hot Face Temp. 86.2 °C   Temp Diff. 75.8
Cold Face Temp. 10.4 °C   Ave. Temp. Diff. 75.28

Date April 20, 1950

Test No. 310

MATERIAL/SIZE: As Above

Wt. Test Box	194.5	Total Power	215
Wt. Test Box & Samples	279.1	Average Power	107.5
Wt. 2 Samples	84.6	Average Wt. Sample	42.3

POTENTIOMETER:

Ref. Junc. Temp. 19.8 °C = .78 mv
Hot Face Corr. Read. 3.34 mv = 80.75 °C
Cold Face Corr. Read. .37 mv = 9.50 °C
Temp. Diff. 71.25

RECORDER:

Hot Face Temp. 83 °C   Temp Diff. 72.2
Cold Face Temp. 10.8 °C   Ave. Temp. Diff. 71.72

THERMAL CONDUCTIVITY TEST

Date April 20, 1950

Test No. 311

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box 194.5
Wt. Test Box & Samples 279.8
Wt. 2 Samples 85.3

Total Power 220
Average Power 110
Average Wt. Sample 42.6

POTENTIOMETER:

Ref. Junc. Temp. 23 °C = .91 mv
Hot Face Corr. Read. 3.40 mv = 81.0 °C
Cold Face Corr. Read. .41 mv = 10.5 °C
Temp. Diff. 71.5

RECORDER:

Hot Face Temp. 82.1 °C
Cold Face Temp. 11.0 °C
Temp Diff. 71.1
Ave. Temp. Diff. 71.3

Date April 21, 1950

Test No. 312

MATERIAL/SIZE: As Above

Wt. Test Box 194.5
Wt. Test Box & Samples 281.0
Wt. 2 Samples 86.5

Total Power 220
Average Power 110
Average Wt. Sample 43.2

POTENTIOMETER:

Ref. Junc. Temp. 24.8 °C = .98 mv
Hot Face Corr. Read. 3.36 mv = 80.00 °C
Cold Face Corr. Read. .34 mv = 8.75 °C
Temp. Diff. 71.25

RECORDER:

Hot Face Temp. 81.4 °C
Cold Face Temp. 10.6 °C
Temp Diff. 70.8
Ave. Temp. Diff. 71.02

THERMAL CONDUCTIVITY TEST

Date *April 21,* 1950

Test No. *313*

MATERIAL/SIZE: *Cow Bay Sand .25mm., lower*

Wt. Test Box	*194.5*	Total Power	*226*
Wt. Test Box & Samples	*281.1*	Average Power	*113*
Wt. 2 Samples	*86.6*	Average Wt. Sample	*43.3*

POTENTIOMETER:

Ref. Junc. Temp. *22.7* °C = *.90* mv Temp.
Hot Face Corr. Read. *3.44* mv = *81.8* °C Diff. *72.05*
Cold Face Corr. Read. *.38* mv = *9.75* °C

RECORDER:

Hot Face Temp. *84.6* °C Temp Diff. *72.6*
Cold Face Temp. *12.0* °C Ave. Temp. Diff. *72.28*

Date *April 22,* 1950

Test No. *314*

MATERIAL/SIZE: *As Above*

Wt. Test Box	*194.5*	Total Power	*213*
Wt. Test Box & Samples	*282.6*	Average Power	*106.5*
Wt. 2 Samples	*88.1*	Average Wt. Sample	*44.0*

POTENTIOMETER:

Ref. Junc. Temp. *24.0* °C = *.95* mv Temp.
Hot Face Corr. Read. *3.27* mv = *78.0* °C Diff. *67.75*
Cold Face Corr. Read. *.40* mv = *10.25* °C

RECORDER:

Hot Face Temp. *79.6* °C Temp Diff. *68.0*
Cold Face Temp. *11.6* °C Ave. Temp. Diff. *67.88*

THERMAL CONDUCTIVITY TEST

Date April 22, 1950

Test No. 315

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box 194.5
Wt. Test Box & Samples 282.9
Wt. 2 Samples 88.4

Total Power 222
Average Power 111
Average Wt. Sample 44.2

POTENTIOMETER:

Ref. Junc. Temp. 23 °C = .91 mv
Hot Face Corr. Read. 3.40 mv = 81.0 °C
Cold Face Corr. Read. .41 mv = 10.5 °C

Temp. Diff. 70.5

RECORDER:

Hot Face Temp. 82.2 °C
Cold Face Temp. 11.8 °C

Temp Diff. 70.4
Ave. Temp. Diff. 70.45

Date April 23, 1950

Test No. 316

MATERIAL/SIZE: As Above

Wt. Test Box 194.5
Wt. Test Box & Samples 286.0
Wt. 2 Samples 91.5

Total Power 220
Average Power 110
Average Wt. Sample 45.8

POTENTIOMETER:

Ref. Junc. Temp. 21 °C = .83 mv
Hot Face Corr. Read. 3.27 mv = 78.0 °C
Cold Face Corr. Read. .41 mv = 10.5 °C

Temp. Diff. 67.5

RECORDER:

Hot Face Temp. 79.0 °C
Cold Face Temp. 11.5 °C

Temp Diff. 67.5
Ave. Temp. Diff. 67.5

THERMAL CONDUCTIVITY TEST

Date April 23, 1950

Test No. 317

MATERIAL/SIZE: Cow Bay Sand .25 mm., lower

Wt. Test Box 194.5
Wt. Test Box & Samples 288.0
Wt. 2 Samples 93.5

Total Power 228
Average Power 114
Average Wt. Sample 46.8

POTENTIOMETER:

Ref. Junc. Temp. 25.4 °C = 1.01 mv
Hot Face Corr. Read. 3.17 mv = 75.8 °C
Cold Face Corr. Read. .41 mv = 10.5 °C
Temp. Diff. 65.3

RECORDER:

Hot Face Temp. 76.1 °C
Cold Face Temp. 11.2 °C
Temp Diff. 64.9
Ave. Temp. Diff. 65.1

Date April 24, 1950

Test No. 318

MATERIAL/SIZE: As Above

Wt. Test Box 194.5
Wt. Test Box & Samples 289.6
Wt. 2 Samples 95.1

Total Power 222
Average Power 111
Average Wt. Sample 47.6

POTENTIOMETER:

Ref. Junc. Temp. 19.8 °C = .78 mv
Hot Face Corr. Read. 3.07 mv = 73.6 °C
Cold Face Corr. Read. .38 mv = 9.75 °C
Temp. Diff. 63.85

RECORDER:

Hot Face Temp. 74.2 °C
Cold Face Temp. 10.6 °C
Temp Diff. 63.6
Ave. Temp. Diff. 63.72

THERMAL CONDUCTIVITY TEST

Date April 26, 1950

Test No. 3-A

MATERIAL/SIZE: Cow Bay Sand .25 mm. lower

Wt. Test Box	194.0	Total Power	220
Wt. Test Box & Samples	271.0	Average Power	110
Wt. 2 Samples	77.0	Average Wt. Sample	38.5

POTENTIOMETER:

Ref. Junc. Temp.	17 °C	= .67 mv	Temp. Diff.	84.8
Hot Face Corr. Read.	3.99 mv	= 93.8 °C		
Cold Face Corr. Read.	.35 mv	= 9.0 °C		

RECORDER:

Hot Face Temp.	95.4 °C	Temp Diff.	84.9
Cold Face Temp.	10.5 °C	Ave. Temp. Diff.	84.85

Date April 27, 1950

Test No. 3-B

MATERIAL/SIZE: As Above

Wt. Test Box	194.0	Total Power	224
Wt. Test Box & Samples	274.0	Average Power	112
Wt. 2 Samples	80.0	Average Wt. Sample	40.0

POTENTIOMETER:

Ref. Junc. Temp.	20.8 °C	= .82 mv	Temp. Diff.	78.15
Hot Face Corr. Read.	3.74 mv	= 88.4 °C		
Cold Face Corr. Read.	.40 mv	= 10.25 °C		

RECORDER:

Hot Face Temp.	91.2 °C	Temp Diff.	79.8
Cold Face Temp.	11.4 °C	Ave. Temp. Diff.	78.98

THERMAL CONDUCTIVITY TEST

Date April 27, 1950

Test No. 3C

MATERIAL/SIZE: Cow Boy Sand .25mm. lower

Wt. Test Box	194.0	Total Power	230
Wt. Test Box & Samples	277.8	Average Power	115
Wt. 2 Samples	83.8	Average Wt. Sample	41.9

POTENTIOMETER:

Ref. Junc. Temp. 20 °C = .79 mv Temp.
Hot Face Corr. Read. 3.69 mv = 87.4 °C Diff. 77.4
Cold Face Corr. Read. .39 mv = 10.0 °C

RECORDER:

Hot Face Temp. 89.6 °C Temp Diff. 77.6
Cold Face Temp. 12.0 °C Ave. Temp. Diff. 77.5

Date April 28, 1950

Test No. 3-D

MATERIAL/SIZE: As Above

Wt. Test Box	194.0	Total Power	212
Wt. Test Box & Samples	279.4	Average Power	106
Wt. 2 Samples	85.4	Average Wt. Sample	42.7

POTENTIOMETER:

Ref. Junc. Temp. 21.5 °C = .85 mv Temp.
Hot Face Corr. Read. 3.39 mv = 80.75 °C Diff. 71.25
Cold Face Corr. Read. .37 mv = 9.50 °C

RECORDER:

Hot Face Temp. 82.7 °C Temp Diff. 71.2
Cold Face Temp. 11.5 °C Ave. Temp. Diff. 71.22

THERMAL CONDUCTIVITY TEST

Date *April 28,* 1950

Test No. *3-E*

MATERIAL/SIZE: *Cow Bay Sand .25 mm. lower*

Wt. Test Box *194.0*
Wt. Test Box & Samples *284.5*
Wt. 2 Samples *90.5*

Total Power *223*
Average Power *111.5*
Average Wt. Sample *45.25*

POTENTIOMETER:

Ref. Junc. Temp. *23.2* °C = *.88* mv
Hot Face Corr. Read. *3.25* mv = *77.6* °C
Cold Face Corr. Read. *.36* mv = *9.25* °C
Temp. Diff. *68.35*

RECORDER:

Hot Face Temp. *80.1* °C   Temp Diff. *68.1*
Cold Face Temp. *12.0* °C   Ave. Temp. Diff. *68.22*

Date ______ 1950

Test No. ______

MATERIAL/SIZE: ______

Wt. Test Box ______
Wt. Test Box & Samples ______
Wt. 2 Samples ______

Total Power ______
Average Power ______
Average Wt. Sample ______

POTENTIOMETER:

Ref. Junc. Temp. ______ °C = ______ mv
Hot Face Corr. Read. ______ mv = ______ °C
Cold Face Corr. Read. ______ mv = ______ °C
Temp. Diff. ______

RECORDER:

Hot Face Temp. ______ °C   Temp Diff. ______
Cold Face Temp. ______ °C   Ave. Temp. Diff. ______

THERMAL CONDUCTIVITY TEST

Date MAY 5 1950

Test No. 401

MATERIAL/SIZE: CLAY - WELL GRADED

Wt. Test Box 194.2
Wt. Test Box & Samples 254.7
Wt. 2 Samples 60.5

Total Power 140
Average Power 70
Average Wt. Sample 30.25

POTENTIOMETER:

Ref. Junc. Temp. 24.0 °C = .95 mv
Hot Face Corr. Read. 3.32 mv = 79.2 °C
Cold Face Corr. Read. .50 mv = 12.75 °C

Temp. Diff. 66.45

RECORDER:

Hot Face Temp. 79.4 °C
Cold Face Temp. 13.0 °C

Temp Diff. 66.4
Ave. Temp. Diff. 66.42

Date MAY 6 1950

Test No. 402

MATERIAL/SIZE: AS ABOVE

Wt. Test Box 194.2
Wt. Test Box & Samples 255.6
Wt. 2 Samples 61.4

Total Power 158
Average Power 79
Average Wt. Sample 30.7

POTENTIOMETER:

Ref. Junc. Temp. 22.8 °C = .90 mv
Hot Face Corr. Read. 3.52 mv = 83.6 °C
Cold Face Corr. Read. .47 mv = 12.0 °C

Temp. Diff. 71.6

RECORDER:

Hot Face Temp. 83.9 °C
Cold Face Temp. 12.0 °C

Temp Diff. 71.9
Ave. Temp. Diff. 71.75

THERMAL CONDUCTIVITY TEST

Date May 6 1950

Test No. 403

MATERIAL/SIZE: CLAY - WELL GRADED

Wt. Test Box 194.2
Wt. Test Box & Samples 256.6
Wt. 2 Samples 62.4 ~~64.2~~

Total Power 160
Average Power 80
Average Wt. Sample 31.2

POTENTIOMETER:

Ref. Junc. Temp. 21.3 °C = .84 mv
Hot Face Corr. Read. 3.44 mv = 81.8 °C
Cold Face Corr. Read. .47 mv = 12.0 °C

Temp. Diff. 69.8

RECORDER:

Hot Face Temp. 82.5 °C
Cold Face Temp. 12.4 °C

Temp Diff. 70.4
Ave. Temp. Diff. 69.95

Date MAY 7 1950

Test No. 404

MATERIAL/SIZE: AS ABOVE

Wt. Test Box 194.2
Wt. Test Box & Samples 258.0
Wt. 2 Samples 63.8

Total Power 153
Average Power 76.5
Average Wt. Sample 31.9

POTENTIOMETER:

Ref. Junc. Temp. 18.0 °C = .77 mv
Hot Face Corr. Read. 3.34 mv = 79.6 °C
Cold Face Corr. Read. .46 mv = 11.75 °C

Temp. Diff. 67.85

RECORDER:

Hot Face Temp. 79.0 °C
Cold Face Temp. 11.0 °C

Temp Diff. 68.0
Ave. Temp. Diff. 67.92

THERMAL CONDUCTIVITY TEST

Date MAY 7 1950

Test No. 405

MATERIAL/SIZE: CLAY - WELL GRADED

Wt. Test Box 194.2
Wt. Test Box & Samples 258.6
Wt. 2 Samples 64.4

Total Power 153
Average Power 76.5
Average Wt. Sample 32.2

POTENTIOMETER:

Ref. Junc. Temp. 23.0 °C = .91 mv
Hot Face Corr. Read. 3.19 mv = 16.25 °C
Cold Face Corr. Read. .49 mv = 12.50 °C

Temp. Diff. 63.75

RECORDER:

Hot Face Temp. 76.1 °C
Cold Face Temp. 12.0 °C

Temp Diff. 64.1
Ave. Temp. Diff. 63.92

Date MAY 8 1950

Test No. 406

MATERIAL/SIZE:

Wt. Test Box 194.2
Wt. Test Box & Samples 260.0
Wt. 2 Samples 65.8

Total Power 155
Average Power 77.5
Average Wt. Sample 32.9

POTENTIOMETER:

Ref. Junc. Temp. 22.8 °C = .90 mv
Hot Face Corr. Read. 3.23 mv = 77.2 °C
Cold Face Corr. Read. .46 mv = 12.75 °C

Temp. Diff. 65.45

RECORDER:

Hot Face Temp. 78.4 °C
Cold Face Temp. 13.4 °C

Temp Diff. 65.0
Ave. Temp. Diff. 65.22

THERMAL CONDUCTIVITY TEST

Date MAY 9 1950

Test No. 407

MATERIAL/SIZE: Clay - Well Graded

Wt. Test Box 194.2
Wt. Test Box & Samples 261.3
Wt. 2 Samples 67.1

Total Power 152
Average Power 76
Average Wt. Sample 33.55

POTENTIOMETER:

Ref. Junc. Temp. 23.0 °C = .91 mv
Hot Face Corr. Read. 3.13 mv = 75.0 °C
Cold Face Corr. Read. .45 mv = 11.5 °C

Temp. Diff. 63.5

RECORDER:

Hot Face Temp. 75.2 °C
Cold Face Temp. 12.8 °C

Temp Diff. 62.4
Ave. Temp. Diff. 62.95

Date MAY 9 1950

Test No. 408

MATERIAL/SIZE: As Above

Wt. Test Box 194.2
Wt. Test Box & Samples 263.1
Wt. 2 Samples 68.9

Total Power 156
Average Power 78
Average Wt. Sample 34.45

POTENTIOMETER:

Ref. Junc. Temp. 24.0 °C = .95 mv
Hot Face Corr. Read. 3.02 mv = 72.5 °C
Cold Face Corr. Read. .46 mv = 11.75 °C

Temp. Diff. 60.75

RECORDER:

Hot Face Temp. 72.8 °C
Cold Face Temp. 13.4 °C

Temp Diff. 59.4
Ave. Temp. Diff. 60.08

THERMAL CONDUCTIVITY TEST

Date MAY 10 1950

Test No. 409

MATERIAL/SIZE: Clay - Well Graded

Wt. Test Box 194.2
Wt. Test Box & Samples 264.7
Wt. 2 Samples 70.5

Total Power 158
Average Power 79
Average Wt. Sample 35.25

POTENTIOMETER:

Ref. Junc. Temp. 24.6 °C = .97 mv
Hot Face Corr. Read. 2.96 mv = 71.2 °C
Cold Face Corr. Read. .49 mv = 12.5 °C
Temp. Diff. 58.7

RECORDER:

Hot Face Temp. 72.1 °C
Cold Face Temp. 13.6 °C
Temp Diff. 58.5
Ave. Temp. Diff. 58.6

Date MAY 11 1950

Test No. 410

MATERIAL/SIZE: As Above

Wt. Test Box 194.2
Wt. Test Box & Samples 266.5
Wt. 2 Samples 72.3

Total Power 160
Average Power 80
Average Wt. Sample 36.15

POTENTIOMETER:

Ref. Junc. Temp. 24.5 °C = .97 mv
Hot Face Corr. Read. 2.96 mv = 71.2 °C
Cold Face Corr. Read. .50 mv = 12.75 °C
Temp. Diff 58.45

RECORDER:

Hot Face Temp. 72.1 °C
Cold Face Temp. 13.9 °C
Temp Diff. 58.2
Ave. Temp. Diff. 58.32

THERMAL CONDUCTIVITY TEST

Date MAY 11 1950

Test No. 411

MATERIAL/SIZE: Clay- Well Graded

Wt. Test Box 194.2
Wt. Test Box & Samples 267.5
Wt. 2 Samples 73.3

Total Power 153
Average Power 76.5
Average Wt. Sample 36.65

POTENTIOMETER:

Ref. Junc. Temp. 22.3 °C = .88 mv
Hot Face Corr. Read. 2.87 mv = 69.2 °C
Cold Face Corr. Read. .49 mv = 12.5 °C
Temp. Diff. 56.7

RECORDER:

Hot Face Temp. 70.0 °C
Cold Face Temp. 14.0 °C
Temp Diff. 56.0
Ave. Temp. Diff. 56.35

Date MAY 12 1950

Test No. 412

MATERIAL/SIZE: As Above

Wt. Test Box 194.2
Wt. Test Box & Samples 269.0
Wt. 2 Samples 74.8

Total Power 152
Average Power 76
Average Wt. Sample 37.4

POTENTIOMETER:

Ref. Junc. Temp. 22.3 °C = .88 mv
Hot Face Corr. Read. 2.80 mv = 67.5 °C
Cold Face Corr. Read. .50 mv = 12.75 °C
Temp. Diff. 54.75

RECORDER:

Hot Face Temp. 68.5 °C
Cold Face Temp. 14.4 °C
Temp Diff. 54.1
Ave. Temp. Diff. 54.42

THERMAL CONDUCTIVITY TEST

Date *May 13* 1950

Test No. *4/3*

MATERIAL/SIZE: *Clay - Well Graded*

Wt. Test Box *194.2*
Wt. Test Box & Samples *271.5*
Wt. 2 Samples *77.3*

Total Power *150*
Average Power *75*
Average Wt. Sample *38.65*

POTENTIOMETER:

Ref. Junc. Temp. *22.2* °C = *.88* mv
Hot Face Corr. Read. *2.70* mv = *65.25* °C
Cold Face Corr. Read. *.49* mv = *12.50* °C
Temp. Diff. *52.75*

RECORDER:

Hot Face Temp. *66.2* °C
Cold Face Temp. *14.2* °C
Temp Diff. *52.0*
Ave. Temp. Diff. *52.38*

Date *May 16* 1950

Test No. *4-A*

MATERIAL/SIZE: *As Above*

Wt. Test Box *193.8*
Wt. Test Box & Samples *257.4*
Wt. 2 Samples *63.6*

Total Power *148*
Average Power *74*
Average Wt. Sample *31.8*

POTENTIOMETER:

Ref. Junc. Temp. *19.0* °C = *.75* mv
Hot Face Corr. Read. *3.23* mv = *77.2* °C
Cold Face Corr. Read. *.54* mv = *13.75* °C
Temp. Diff. *63.45*

RECORDER:

Hot Face Temp. *77.75* °C
Cold Face Temp. *14.00* °C
Temp Diff. *63.75*
Ave. Temp. Diff. *63.60*

THERMAL CONDUCTIVITY TEST

Date MAY 17 1950

Test No. 4-B

MATERIAL/SIZE: Clay - Well Graded

Wt. Test Box 193.8 Total Power 148
Wt. Test Box & Samples 258.4 Average Power 74
Wt. 2 Samples 64.7 Average Wt. Sample 32.35

POTENTIOMETER:

Ref. Junc. Temp. 24.5 °C = .97 mv
Hot Face Corr. Read. 3.17 mv = 75.8 °C Temp. Diff. 61.55
Cold Face Corr. Read. .56 mv = 14.25 °C

RECORDER:

Hot Face Temp. 75.6 °C Temp Diff. 61.9
Cold Face Temp. 13.7 °C Ave. Temp. Diff. 61.72

Date MAY 18 1950

Test No. 4-C

MATERIAL/SIZE: As Above

Wt. Test Box 193.8 Total Power 156
Wt. Test Box & Samples 261.3 Average Power 78
Wt. 2 Samples 67.5 Average Wt. Sample 33.75

POTENTIOMETER:

Ref. Junc. Temp. 20.8 °C = .82 mv
Hot Face Corr. Read. 3.17 mv = 75.80 °C Temp. Diff. 62.05
Cold Face Corr. Read. .54 mv = 13.75 °C

RECORDER:

Hot Face Temp. 76.3 °C Temp Diff. 62.3
Cold Face Temp. 14.0 °C Ave. Temp. Diff. 62.18

TABLE I
EXPERIMENTAL RESULTS FOR COARSE SAND
2.0 mm. - .42 mm.

Test No.	Avg. Wt.	Avg. Power	Avg. Temp. Diff.	e	K x 10^4
101	42.00	83.5	53.00	.832	7.31
1A	42.70	125.0	71.00	.801	8.19
102	42.75	110.0	65.25	.799	7.84
103	43.40	110.0	62.00	.773	8.26
104	43.80	106.0	59.72	.756	8.27
105	44.40	111.0	59.25	.733	8.72
1B	44.75	125.0	66.80	.720	8.70
106	44.90	112.5	56.38	.714	9.30
107	45.35	110.0	58.12	.697	8.83
108	45.80	110.0	57.50	.680	8.91
109	46.30	107.5	55.05	.662	9.09
1C	46.90	125.0	63.00	.640	9.24
110	47.00	109.0	55.00	.637	9.21
111	48.70	110.0	52.00	.578	9.85

Thickness of sample 5.05 cm.
Area of sample 2597 $cm.^2$
Specific Gravity of sample 2.66
Moisture Content Initial .0589% Final .0416%
Material Placed Two Times

TABLE II
EXPERIMENTAL RESULTS FOR MEDIUM SAND
.42 mm.-.25mm.

Test No.	Avg. Wt.	Avg. Power	Avg. Temp. Diff.	e	$K \times 10^4$
201	39.20	110.0	73.72	.970	6.95
2A	39.45	105.0	71.38	.960	6.84
251	39.70	105.0	74.18	.943	6.58
2B	39.95	110.0	72.25	.932	7.08
252	40.25	110.0	73.78	.919	6.95
202	40.90	110.0	73.00	.890	7.02
253	41.05	114.0	75.72	.880	7.02
254	41.50	110.0	71.92	.861	7.12
203	41.90	110.0	70.38	.842	7.28
2C	42.10	106.0	65.22	.835	7.55
255	42.25	110.0	69.95	.829	7.32
204	42.45	110.0	69.78	.827	7.35
205	43.15	110.0	67.25	.788	7.61
256	43.65	114.0	67.65	.772	7.82
206	43.90	110.0	65.50	.761	7.82
207	44.75	114.0	66.25	.725	8.00
2D	45.05	112.5	63.75	.715	8.21
257	45.50	113.5	65.78	.697	8.03

Thickness of sample 5.05 cm.
Area of sample 2597 $cm.^2$
Specific Gravity of sample 2.675
Moisture Content Initial .0508% Final .0387%
Material Placed Three times

TABLE III
EXPERIMENTAL RESULTS FOR FINE SAND

Test No.	Avg. Wt.	Avg. Power	Avg. Temp. Diff.	e	K x 10^4
301	38.30	110.0	80.28	1.046	6.38
3A	38.50	110.0	84.85	1.035	6.04
302	38.60	110.0	77.38	1.032	6.62
303	39.20	110.0	80.40	1.000	6.37
304	39.50	110.0	78.82	0.985	6.50
3B	40.00	111.0	78.53	0.960	6.58
305	40.10	112.0	78.98	0.955	6.60
306	40.50	115.0	79.20	0.936	6.74
307	41.00	113.5	79.85	0.912	6.62
308	41.10	110.0	75.73	0.907	6.77
309	41.70	110.0	74.75	0.880	6.85
3C	41.90	116.0	77.75	0.871	6.88
310	42.30	107.5	71.73	0.853	6.98
311	42.60	110.0	71.30	0.840	7.18
3D	42.70	106.0	71.22	0.836	6.92
312	43.20	110.0	71.03	0.814	7.20
313	43.30	113.0	72.32	0.810	7.18
314	44.00	106.5	67.88	0.782	7.30
315	44.20	111.0	70.45	0.773	7.33
3E	45.25	111.5	68.22	0.732	7.60
316	45.75	110.0	67.50	0.714	7.58
317	46.75	114.0	65.10	0.677	8.13
318	47.50	111.0	63.72	0.651	8.11

Thickness of sample 5.05 cm.
Area of Sample 2597 $cm.^2$
Specific Gravity of sample 2.71
Moisture Content Initial .1425% Final .0921%
Sample Placed Two Times

TABLE IV
EXPERIMENTAL RESULTS FOR CLAY

Test No.	Avg. Wt.	Avg. Power	Avg. Temp. Diff.	e	K x 10^4
401	30.25	70.0	66.42	1.600	4.80
402	30.70	79.0	71.75	1.563	5.12
403	31.20	80.0	69.95	1.522	5.32
4A	31.80	74.0	63.60	1.474	5.41
404	31.90	76.5	67.92	1.468	5.25
405	32.20	76.5	63.92	1.444	5.57
4B	32.35	74.0	61.72	1.434	5.58
406	32.90	77.5	65.48	1.392	5.51
407	33.55	76.0	62.95	1.346	5.61
4C	33.75	78.0	62.18	1.332	5.84
408	34.45	78.0	60.08	1.284	6.04
409	35.25	79.0	58.60	1.232	6.27
410	36.15	80.0	58.32	1.178	6.39
411	36.65	76.5	56.35	1.148	6.32
412	37.40	76.0	54.42	1.195	6.50
413	38.65	75.0	52.38	1.035	6.66

Thickness of sample 5.05 cm.
Area of Sample 2597 $cm.^2$
Specific Gravity of sample 2.725
Moisture Content Initial .1455% Final .0932%
Material Placed Two Times

SAMPLE COMPUTATIONS
Test 101

$$K = \frac{Q\ d}{A\ t\ (T_1 - T_2)} \qquad .....2$$

$$K = \frac{83.5\ \frac{\text{watts}}{\text{sec.}} \times 5.05\ \text{cm.}}{2597\ \text{cm.}^2 \times 1\ \text{sec.} \times 53.0°C \times 4.186\ \frac{\text{watts}}{\text{cal/sec}}}$$

$$K = 7.31\ \text{cal/sec/cm/cm}^2/°C$$

$$e = \frac{V_T\ \ G_s\ (1 + w)}{W_T} - 1 \qquad .....5$$

$$= \frac{20\text{in.}\times 20\text{in.}\times 2\text{in.}\times 2.66\times 62.4\ \frac{\text{lb.}}{\text{ft.}^3}(1 + .00589)}{1728\ \frac{\text{in.}^3}{\text{ft.}^3} \times 42\ \text{lb.}} - 1$$

$$= .832$$

TABLE Ia

STATISTICAL ANALYSIS OF TEST DATA FOR COARSE SAND

Test No.	e	$K \times 10^{-4}$	Dev. e	Dev. K	$(\text{Dev. e})^2$	$(\text{Dev. K})^2$	(Dev. e) x (Dev. K)
101	0.832	7.31	+.116	-1.38	.0134	1.9044	-.1600
1A	0.801	8.19	+.085	-0.50	.0072	0.2500	-.0425
102	0.799	7.84	+.083	-0.85	.0069	.7225	-.0706
103	0.773	8.26	+.057	-0.43	.0032	.1849	-.0235
104	0.756	8.27	+.040	-0.42	.0016	.1764	-.0168
105	0.733	8.72	+.017	+0.03	.0003	.0009	+.0005
1B	0.720	8.70	+.004	+0.01	.0000	.0001	+.0004
106	0.714	9.30	-.002	+0.61	.0000	.3721	-.0012
107	0.697	8.83	-.019	+0.14	.0004	.0196	-.0027
108	0.680	8.91	-.036	+0.22	.0013	.0484	-.0079
109	0.662	9.09	-.054	+0.40	.0029	.1600	-.0022
1C	0.640	9.24	-.076	+0.55	.0057	.3025	-.0042
110	0.637	9.21	-.079	+0.52	.0062	.2704	-.0041
111	0.578	9.85	-.138	+1.16	.0190	.3456	-.1600
	10.022	121.72			.0681	5.7578	-.4948

Number of tests, m = 14

$$\text{mean } \bar{e} = \frac{10.022}{14} = 0.716$$

$$\text{mean } \bar{K} = \frac{121.72}{14} = 8.69 \times 10^{-4} \text{ cal/sec/cm/cm}^2/^\circ\text{C}$$

$$\sigma_e = \sqrt{.0681/14} = .0699 \qquad \sigma_K = \sqrt{5.7578/14} = .642$$

Coefficient of correlation $r_{e.K} = -.4948/14 \times .0699 \times .642 = -.788$

$K = me + b$ and $m_K = (r_{e.K})(\sigma_K/\sigma_e) = -.788\,(.642/.0699) = -7.24$

or $b_K = \bar{K} - m_K\bar{e} = 8.69 - (-7.24)(.716) = +13.87$

Therefore, the equation relating the variables e and K is; $K = -7.24\,e + 13.87$

TABLE IIa
STASTICAL ANALYSIS OF TEST DATA FOR MEDIUM SAND

Test No.	e	$K \times 10^{-4}$	Dev. e	Dev. K	$(\text{Dev. e})^2$	$(\text{Dev. K})^2$	(Dev. e) x (Dev. K)
201	.976	6.95	+.128	-.42	.0164	.1681	-.0525
2A	.960	6.84	+.118	-.52	.0139	.2704	-.0613
251	.943	6.58	+.101	-.78	.0102	.6084	-.0788
2B	.932	7.08	+.090	-.28	.0081	.0786	-.0252
252	.919	6.95	+.077	-.41	.0059	.1681	-.0320
202	.890	7.02	+.048	-.34	.0023	.1156	-.0163
253	.880	7.02	+.038	-.34	.0014	.1156	-.0129
254	.861	7.12	+.019	-.24	.0004	.0576	-.0046
203	.842	7.28	+.000	-.06	.0000	.0036	-.0000
2C	.835	7.55	-.007	+.19	.0000	.0361	-.0013
255	.829	7.32	-.013	-.04	.0002	.0016	+.0005
204	.827	7.35	-.015	-.01	.0002	.0001	+.0001
205	.788	7.61	-.054	+.25	.0029	.0625	-.0014
256	.772	7.82	-.070	+.46	.0049	.2116	-.0032
206	.761	7.82	-.081	+.46	.0066	.2116	-.0037
207	.725	8.00	-.117	+.64	.0137	.4096	-.0750
2D	.715	8.21	-.127	+.85	.0162	.7225	-.1080
257	.697	8.03	-.145	+.67	.0210	.4489	-.0972
	15.146	132.55			.1253	3.6905	-.5728

Number of tests, m = 18 Mean $\bar{e}$ = 15.146/18 = .842

Mean $\bar{K}$ = 132.55/18 = 7.36 x 10^{-4} cal/sec/cm/cm²/°C

$\sigma_e = \sqrt{.1253/18} = .0833$ $\sigma_K = \sqrt{3.6905/18} = .4525$

Coefficient of correlation $r_{e.K} = -.5728/18 \times .0833 \times .4525 = -.842$

$K = me + b$ and $m_K = (r_{e.K})(\sigma_K/\sigma_e) = -.842\ (.4525/.0833) = -4.57$

or $b_K = \bar{K} - m_K\bar{e} = 7.36 - (-4.57)(.842) = 11.21$

Therefore, the equation relating the variable e and K is: $K = -4.57e + 11.21$

TABLE IIIa

STATISTICAL ANALYSIS OF TEST DATA FOR FINE SAND

Test No.	e	$K \times 10^4$	Dev. e	Dev. K	$(\text{Dev. } e)^2$	$(\text{Dev. } K)^2$	(Dev. e) x (Dev. K)
301	1.046	6.38	+.176	-0.60	.0310	0.3600	-.1056
3A	1.035	6.04	+.165	-0.94	.0272	0.8836	-.1551
302	1.032	6.62	+.162	-0.36	.0262	0.1296	-.0583
303	1.000	6.37	+.130	-0.61	.0169	0.3721	-.0793
304	0.985	6.50	+.115	-0.48	.0132	0.2304	-.0552
3B	0.960	6.58	+.040	-0.40	.0016	0.1296	-.0160
305	0.955	6.60	+.085	-0.38	.0072	0.1444	-.0323
306	0.936	6.74	+.066	-0.24	.0044	0.0576	-.0158
307	0.912	6.62	+.042	-0.36	.0018	0.1296	-.0151
308	0.907	6.77	+.037	-0.21	.0014	0.0441	-.0077
309	0.880	6.85	+.010	-0.13	.0001	0.0169	-.0013
3C	0.871	6.88	+.001	-0.10	.0000	0.0100	-.0001
310	0.853	6.98	-.017	+0.00	.0003	0.0000	+.0000
311	0.840	7.18	-.030	+0.20	.0009	0.0400	-.0060
3D	0.836	6.92	-.034	-0.06	.0012	0.0036	+.0020
312	0.814	7.20	-.056	+0.22	.0031	0.0484	-.0123
313	0.810	7.18	-.060	+0.20	.0036	0.0400	-.0120
314	0.782	7.30	-.088	+0.32	.0077	0.1024	-.0282
315	0.773	7,33	-.097	+0.35	.0084	0.1225	-.0340
3E	0.732	7.60	-.138	+0.62	.0190	0.3844	-.0856
316	0.714	7.58	-.156	+0.60	.0243	0.3600	-.0936
317	0.677	8.13	-.193	+1.15	.0377	1.3225	-.2220
318	0.651	8.11	-.219	+1.13	.0479	1.2769	-.4665
	20.001	160.46			.2852	6.2086	-1.4999

Number of tests $m = 23$

$$\text{Mean } \bar{e} = \frac{20.001}{23} = .870$$

$$\text{Mean } \bar{K} = \frac{160.46}{23} = 6.98 \times 10^{-4} \text{ cal/sec/cm/cm}^2/^\circ\text{C}$$

TABLE IIIa (continued)
STATISTICAL ANALYSIS OF TEST DATA FOR FINE SAND

$\sigma_e = \sqrt{.2853/23} = .1114$ $\qquad$ $\sigma_K = \sqrt{6.2086/23} = .520$

Coefficient of correlation $r_{e.K} = -1.4999/23 \times .1114 \times .520 = -1.123$

$K = me + b$ and $m_K = (r_{e.K})(\sigma_K/\sigma_e) = -1.123\ (.520/.1114) = -5.25$

or $b_K = \bar{K} - m_K\bar{e} = 6.98 - (-5.25)(.870) = 11.55$

Therefore, the equation relating the variable e and K is – $K = -5.25\,e + 11.55$

TABLE IVa

STATISTICAL ANALYSIS OF TEST DATA FOR CLAY

Test No.	e	$K \times 10^{-4}$	Dev. e	Dev. K	$(\text{Dev. e})^2$	$(\text{Dev. K})^2$	(Dev. e) x (Dev. K)
401	1.600	4.80	+.253	-.95	.0640	.9025	-.2404
402	1.563	5.12	+.216	-.63	.0467	.3969	-.1361
403	1.522	5.32	+.175	-.43	.0306	.1849	-.0753
4A	1.474	5.41	+.127	-.34	.0162	.1156	-.0432
404	1.468	5.25	+.121	-.50	.0146	.2500	-.0605
405	1.444	5.57	+.097	-.18	.0084	.0324	-.0175
4B	1.434	5.41	+.087	-.34	.0076	.1156	-.0296
406	1.392	5.51	-.045	-.24	.0020	.0576	-.0108
407	1.346	5.61	-.001	-.14	.0000	.0196	+.0001
4C	1.332	5.84	-.015	+.09	.0002	.0081	-.0014
408	1.284	6.04	-.063	+.29	.0040	.0841	-.0183
409	1.232	6.27	-.115	+.52	.0132	.2704	-.0598
410	1.178	6.39	-.169	+.64	.0286	.4096	-.1082
411	1.148	6.32	-.199	+.57	.0396	.3249	-.1144
412	1.105	6.50	-.242	+.75	.0586	.5625	-.1815
413	1.035	6.66	-.312	+.91	.0973	.8281	-.2389
	21.557	92.02			.4316	4.5628	-1.3358

Number of tests m = 16 Mean $\bar{e} = 21.557/16 = 1.347$

Mean $\bar{K} = 92.02/16 = 5.7512$ cal/sec/cm/cm^2/°C

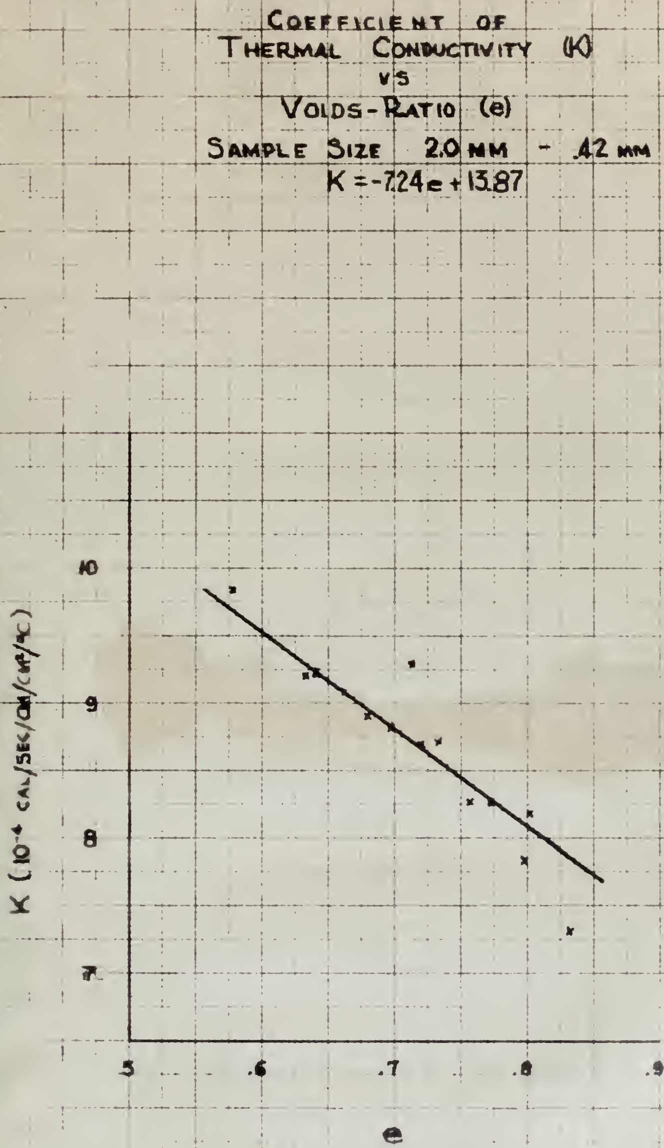
$\sigma_e = \sqrt{.4316/16} = .1642$ $\sigma_K = \sqrt{4.5628/16} = .5340$

Coefficient of correlation $r_{e.K} = -1.3358/16 \times .1642 \times .5340 = -.952$

$K = me + b$ and $m_K = (r_{e.K})(\sigma_K/\sigma_e) = -.952\ (.5340/.1642) = -3.095$

or $b_K = \bar{K} - m_K\bar{e} = 5.751 - (-3.095)(1.347) = 9.91$

Therefore, the equation relating the variable e and K is: $K = -3.095e + 9.91$



COEFFICIENT OF
THERMAL CONDUCTIVITY (K)
VS
VOIDS-RATIO (e)
SAMPLE SIZE 2.0 MM - .42 MM
K = -7.24e + 13.87
K (10⁻⁴ CAL/SEC/CM/CM²/°C)
10
9
8
7
.5
.6
.7
.8
.9
e

FIGURE I

COEFFICIENT OF
THERMAL CONDUCTIVITY (K)
VS.
VOIDS-RATIO (e)
SAMPLE SIZE .42MM-.25MM
$K = -4.57e + 11.21$

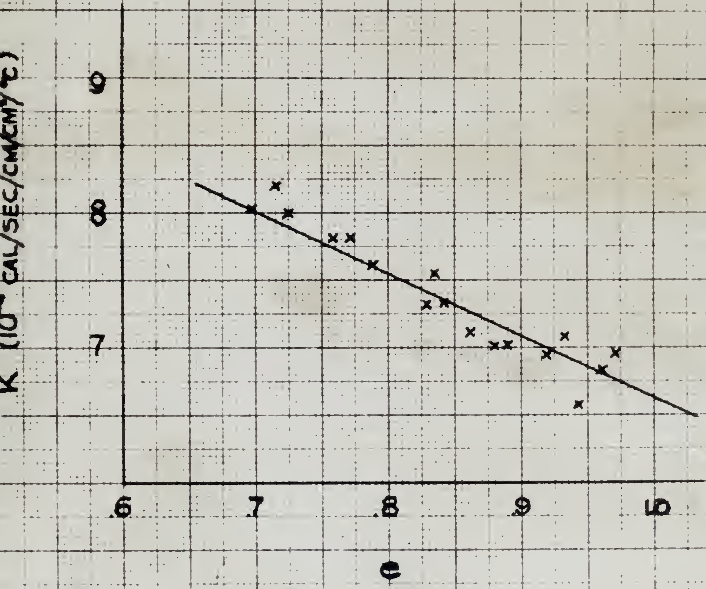


FIGURE II

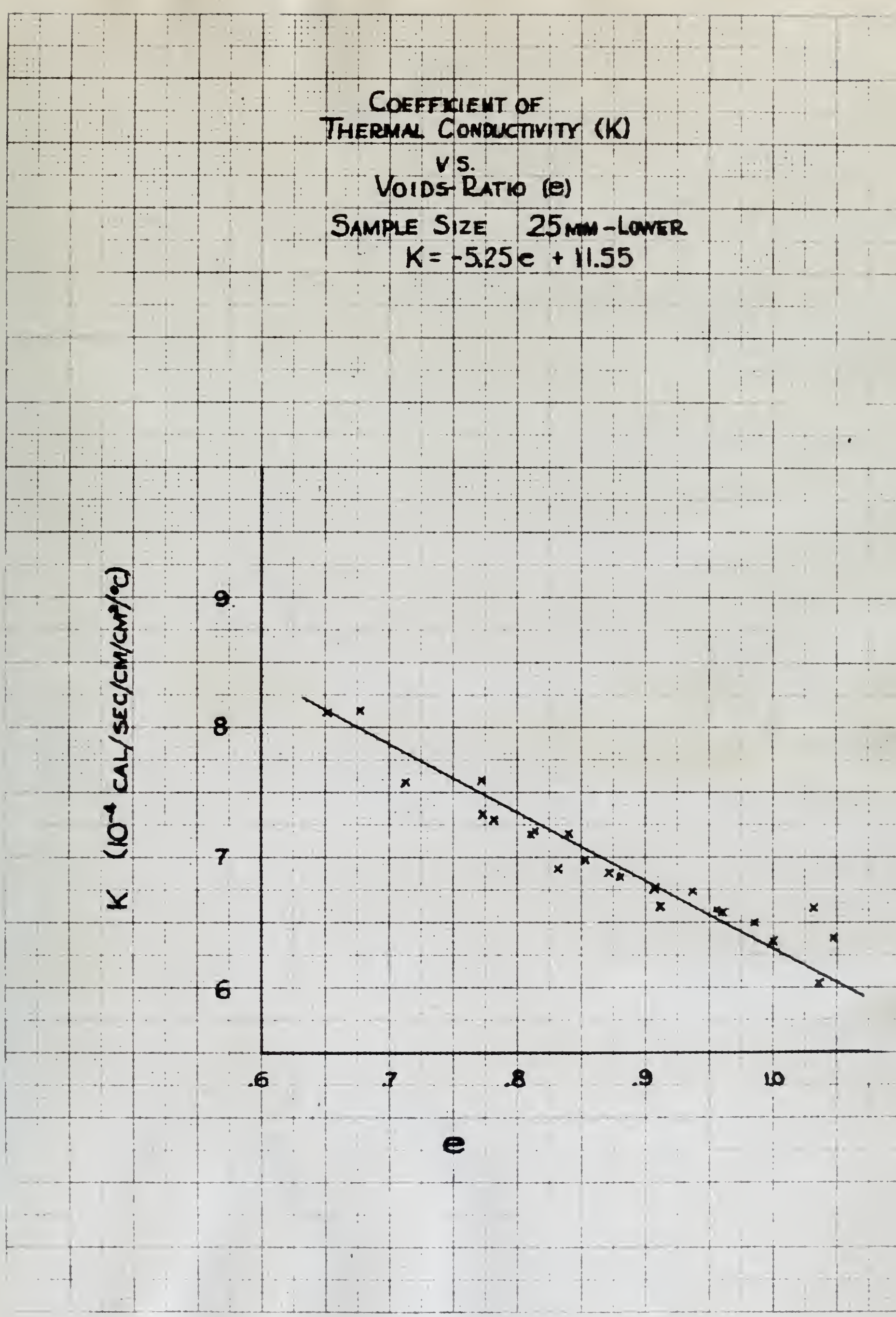

COEFFICIENT OF
THERMAL CONDUCTIVITY (K)
VS.
VOIDS-RATIO (e)
SAMPLE SIZE 25MM-LOWER
K = -5.25e + 11.55
K (10⁻⁴ CAL/SEC/CM/CM²/°C)
9
8
7
6
.6
.7
.8
.9
1.0
e

FIGURE III

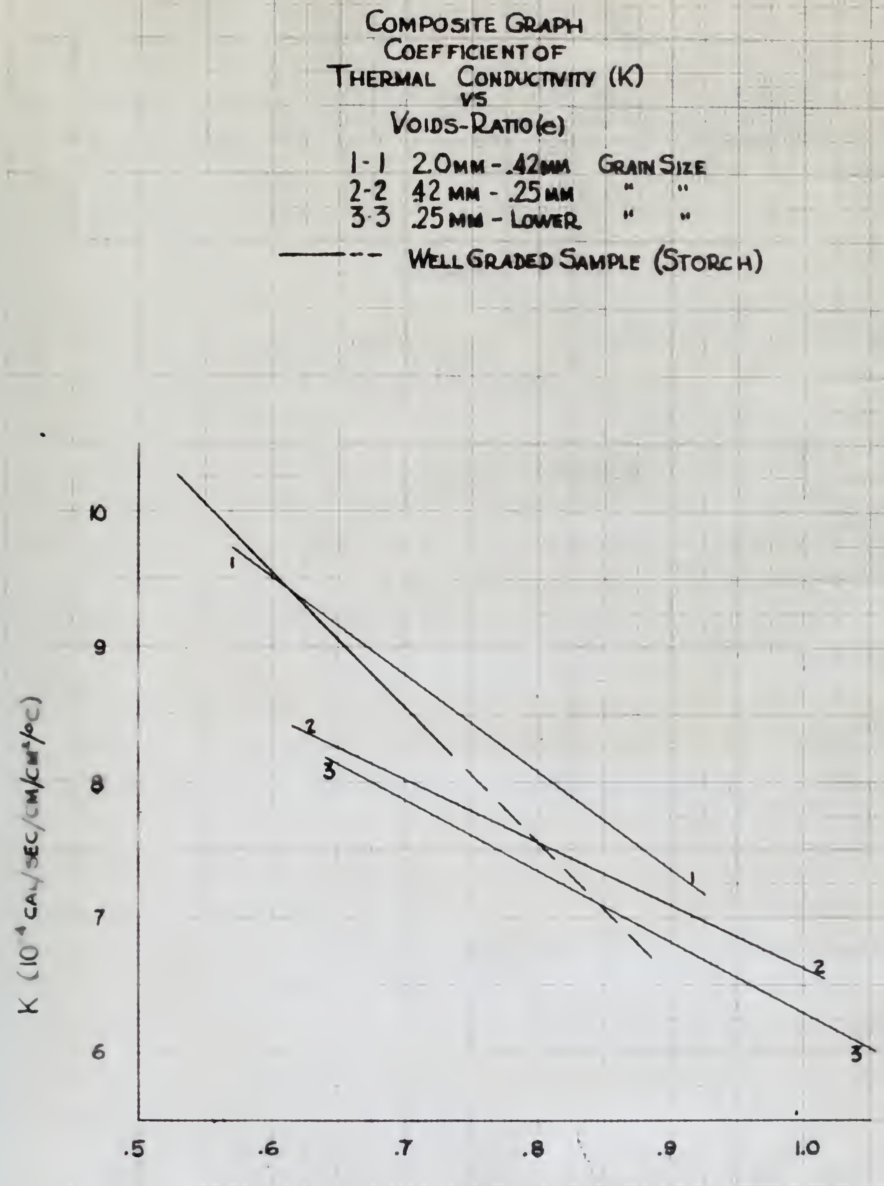

COMPOSITE GRAPH
COEFFICIENT OF
THERMAL CONDUCTIVITY (K)
VS
VOIDS-RATIO (e)
1-1 2.0MM - .42MM GRAIN SIZE
2-2 .42 MM - .25MM " "
3-3 .25MM - LOWER " "
WELL GRADED SAMPLE (STORCH)
K (10^{-4} CAL/SEC/CM/CM²/°C)
10
9
8
7
6
.5
.6
.7
.8
.9
1.0
e
1
1
2
2
3
3

FIGURE IV

COEFFICIENT OF
THERMAL CONDUCTIVITY (K)
VS
VOIDS-RATIO (e)
WELL GRADED CLAY SAMPLE

$K = -3.095e + 9.91$

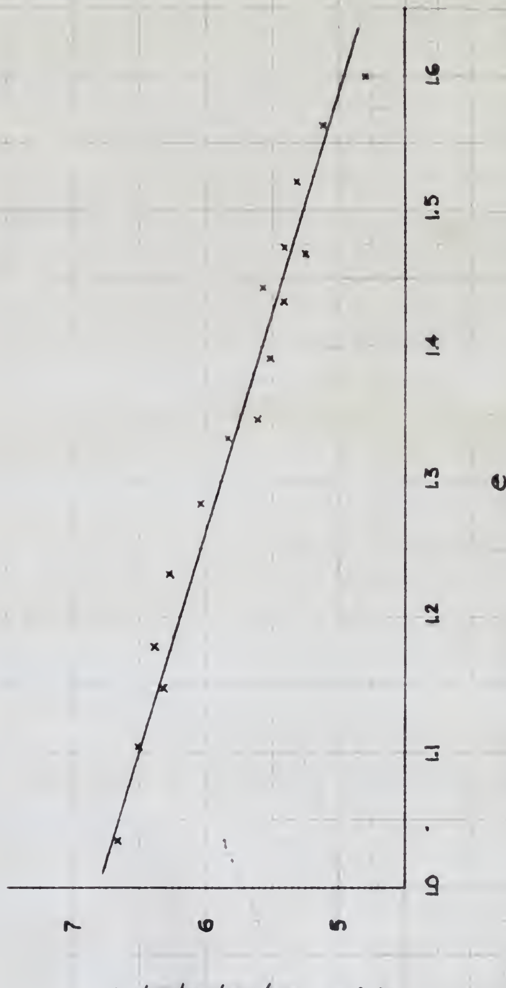


FIGURE V

GRADING CURVE
FOR
CLAY

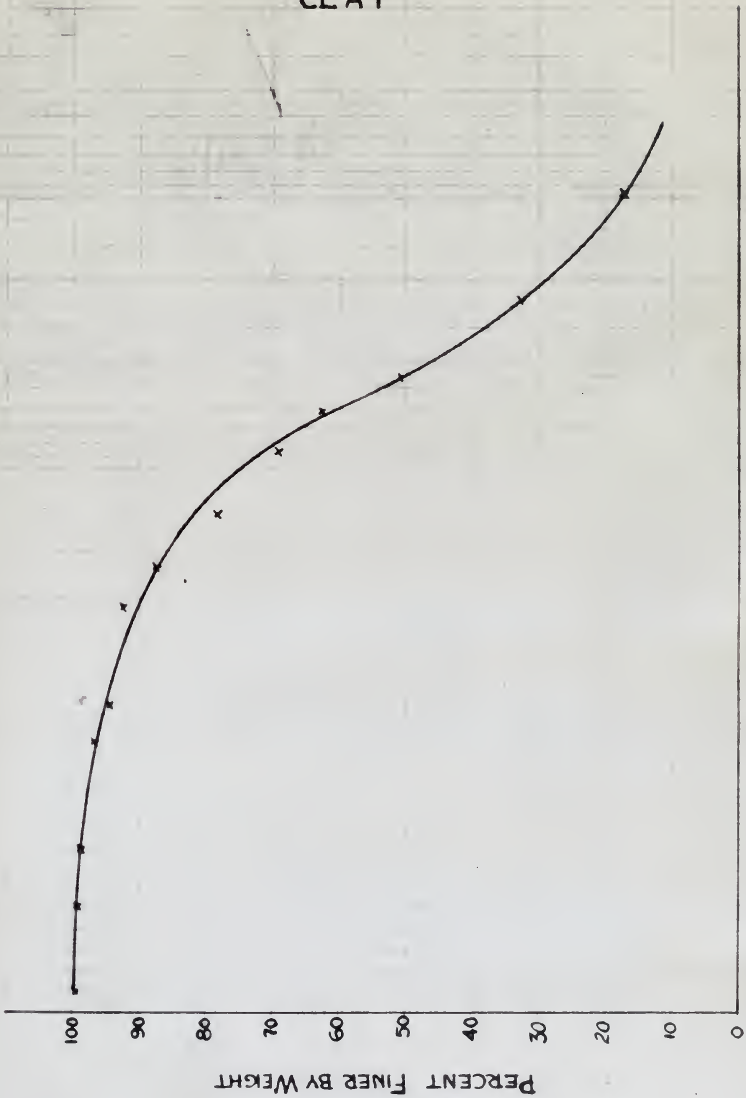
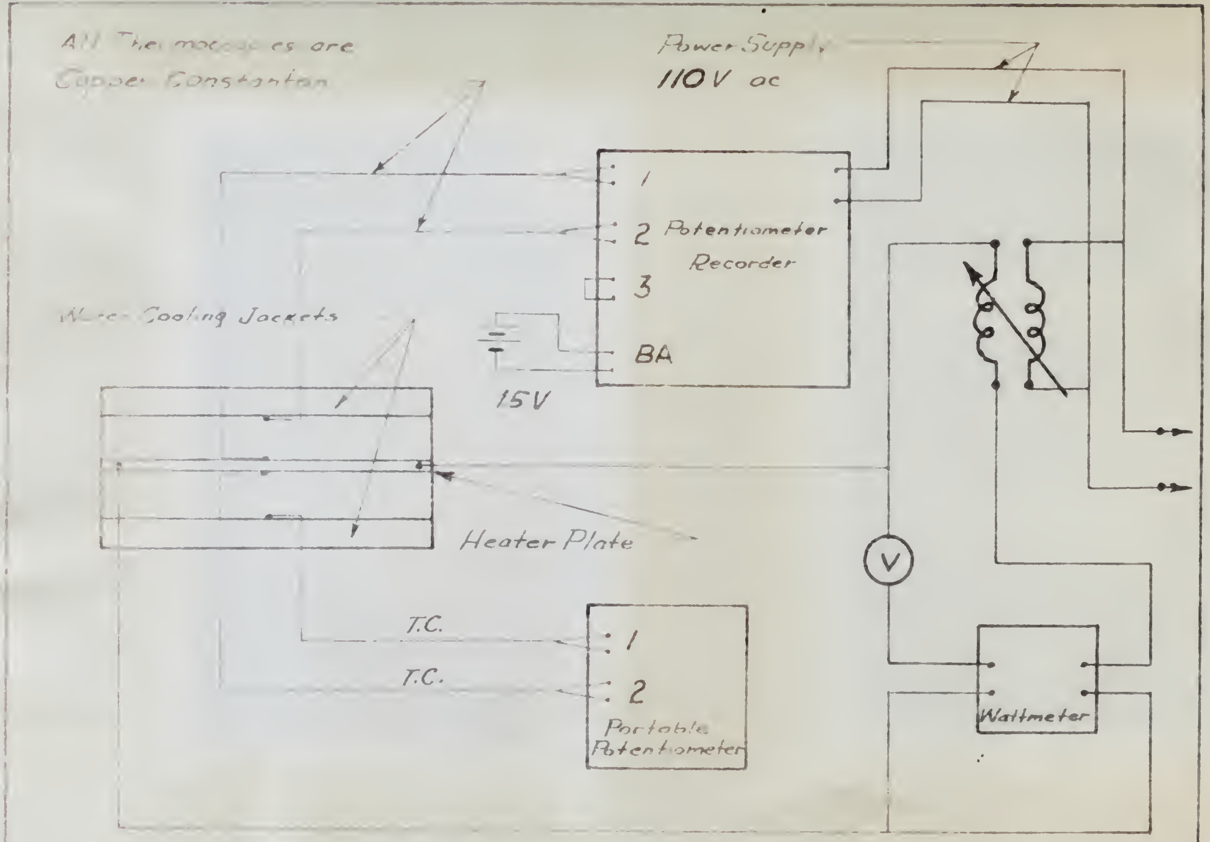


FIGURE VI



SCHEMATIC WIRING DIAGRAM

Figure VII

FIGURE VIIIa Insulating box with cover in place. Mounted on scales.

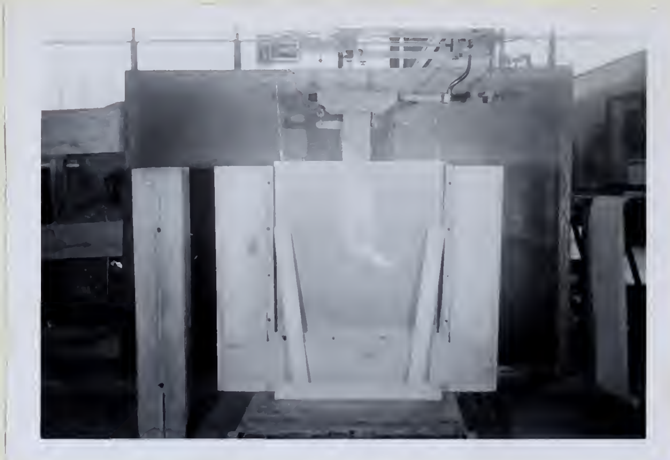


FIGURE VIIIb Insulating box with frame (showing bolt holes) inserted. Heater plate in position with arrow to thermocouple connection. Spacer boards are standing against equipment showing relative position of installation. Insulating box cover at side.

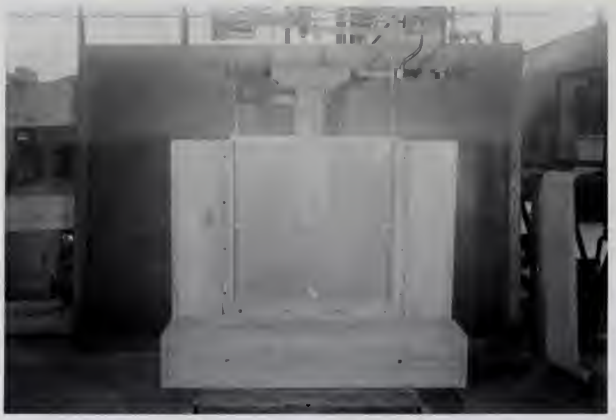


FIGURE VIIIc Insulating box with frame, heater plate and spacer boards in place. Large arrow shows one heating element lead. Small arrows show spacer boards in position.

FIGURE VIIId Sample and insulating boxes completely assembled. Cooling jackets in place with cooling water hoses attached.

FIGURE VIIIe Overall view of equipment showing power leads connected to heating element. Placing and compaction equipment shown near sample box assembly.

FIGURE VIIIf Measuring and control equipment. Potentiometer-Recorder to left. portable potentiometer center. Variac controller upper right, wattmeter lower right.

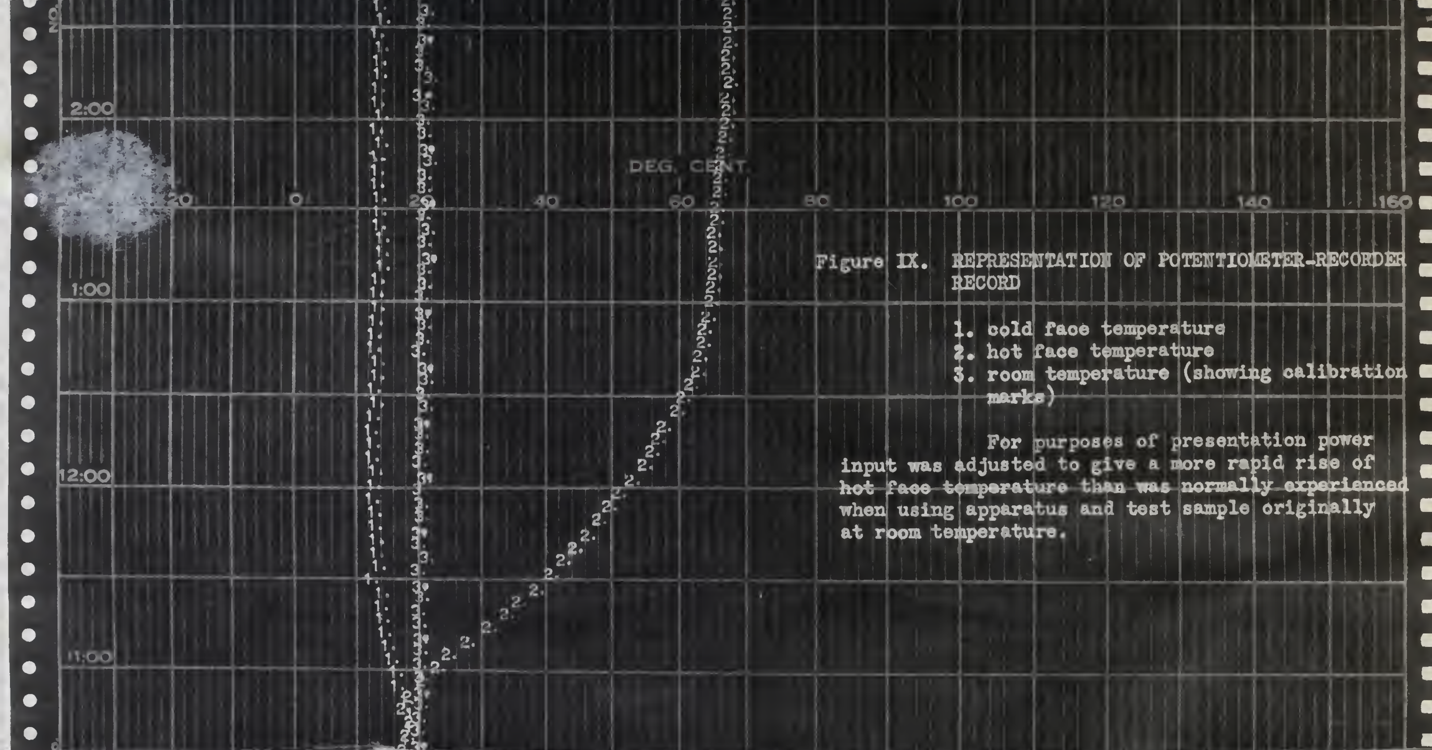


Figure IX. REPRESENTATION OF POTENTIOMETER-RECORDER RECORD

1. cold face temperature
2. hot face temperature
3. room temperature (showing calibration marks)

For purposes of presentation power input was adjusted to give a more rapid rise of hot face temperature than was normally experienced when using apparatus and test sample originally at room temperature.

REFERENCES

1. Storch, Herbert, "An Investigation of the Effects of Voids-Ratio on the Thermal Conductivity of Sands" Troy, N. Y.- May, 1949

2. Kersten, M. S., "Apparatus for Measuring Thermal Conductivity of Soils" and "Thermal Conductivity of Soils" Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering, Volume III Rotterdam, June, 1948

3. Shanklin, G. B., "The Effects of Moisture on the Thermal Conductivity of Soils" Transactions of the American Institute of Electrical Engineers, Volume XLI, 1922

4. Winterkorn, Hans F., "Fundamental Similarities Between Electro-Osmotic and Thermo-Osmotic Phenomena" a Synopsis, Highway Research Board Proceedings, Washington, D. C., December, 1947

5. Reddick, H. W. and Miller, F. H., "Advanced Mathematics for Engineers" Second Edition, New York, John Wiley & Sons, 1947

6. Binder, R. C., "Fluid Mechanics" New York, John Wiley & Sons, 1948

7. Patten, H. E., "Heat Transference in Soils" U. S. Department of Agriculture, Bureau of Soils, Bulletin Number 59, September, 1909

8. "Handbook of Chemistry and Physics" Thirteenth Edition, Cleveland, Chemical Rubber Publishing Company, 1947

9. Hogentogler, C. A., "Engineering Properties of Soil" First Edition, New York, McGraw-Hill Book Co, Inc. 1937